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Vol. VI SEPTEMBER, 1922 Number 7

MAGNETIC ROTATION IN VARIOUS LIQUIDS IN THE SHORT INFRA-RED SPECTRUM

By L. R. Ingersoll

Introduction. This paper describes the results of measurements of magnetic rotation on some forty different liquids in the spectral region between the wave-lengths .56μ and 2.3μ. Approximately half the substances worked with have been aqueous solutions of various salts—mostly of the ferromagnetic metals—and the others pure liquids. Also, mainly to assist in checking the foregoing results with theory, refractive index determinations have been made on the same materials and over the same wave-length range.

While a great deal of work has been done in the field of magnetic rotation in liquids most of the measurements have been confined to the visible spectrum, and in some cases,—e.g. practically all the extensive work of Perkin[1]—to a single wave-length. No attempt will be made at a comprehensive survey of previous results[2] but the work of Quincke,[3] Becquerel,[4] Castleman and Hul-

[1] W. H. Perkin, Jour. Chem. Soc. *36*, p. 330, 1882, and numerous succeeding papers.

[2] For extensive list of references see W. Voigt, Art. "Magneto-optik" in Graetz, "Handb. d. Elektr. u. Magn. vol. 4. Leipzig; 1915.

[3] G. Quincke, Wied. Ann. *24*, p. 606; 1885.

[4] H. Becquerel, C. R., *90* p. 1407, 1880; *100*, p. 1374, 1885; *125*, p. 683, 1897. Ann. Chim. Phys., (5) *12*, p. 42; 1877.

burt,[5] and particularly of Siertsema[6] must be mentioned. Each of these investigators studied a variety of materials, including in some cases negatively rotating liquids such as titaniumtetrachloride and solutions of ferric chloride and potassium ferricyanide. The conclusion was reached that in this latter class of materials the rotation dispersion is much greater than that given by the approximate Verdet law of the inverse square of the wavelength (which holds for the vast majority of substances) and is indeed more nearly proportional to the inverse fourth power.

In the matter of correlation of experiment with magneto-optic theory in this field, Siertsema, among others, has made some interesting progress. Voigt's theory[7] of magnetic rotation on the basis of the inverse Zeeman effect can be shown, on certain assumptions to yield in a region of small absorption the formula

$$\phi = \frac{eH\lambda}{2cm} \cdot \frac{dn}{d\lambda}$$

ϕ being the rotation in radians, n the refractive index, c the velocity of light and e the electronic charge in e.m.u. Lorentz[8] deduces a similar formula. This is of the same type as the Becquerel formula

$$\phi = \kappa\lambda \frac{dn}{d\lambda}$$

With this Siertsema[9] has calculated values of e/m from measurements of magnetic rotation (sodium light) and ordinary dispersion, for a variety of substances. They vary from 1.77×10^7 (approximately the value now accepted on the basis of other determinations) in the case of hydrogen, to somewhat less than half of this for carbon bisulphide. Similar calculations with the aid of an extension of the Lorentz theory have been made by Castleman and Hulburt.[10]

[5] R. A. Castleman, Jr. and E. O. Hulburt, Astrophys. Jour. *54*, p. 45; 1921.

[6] L. H. Siertsema, Leiden Comm. No. 62, 80, 82, 90, 91, and Supp. No. 1. Amst. Proc., *4*, p. 339, 1901–2; *5*, pp. 243, 413, 1902–3; *6*, p. 760, 1903–4; *18*, pp. 101, 925, 1916. Arch. Neer., (2) *5*, p. 447, 1900; *6*, p. 825, 1901.

[7] W. Voigt, *loc. cit.* p. 572.

[8] H. A. Lorentz, "Magneto-optische Phänomene," Ency. d. Math. Wiss. vol. V$_2$, p. 251.

[9] Leiden Comm., No. 82, p. 5.

[10] Astrophys. Jour., *54*, p. 63; 1921.

The present investigation was undertaken for several different reasons. The extension of our knowledge of rotation dispersion over the increased wave-length range afforded by the spectrobolometric method of measurement hardly needs justification. The question of the effect of infra-red absorption bands is one whose answer should be looked for with considerable interest. Also, as indicated by the above formulas, magneto-optic theory connects in intimate fashion magnetic rotation with other optical properties, e.g., ordinary dispersion. These two quantities have as a rule been determined at different times and by different observers with some consequent difficulty and uncertainty in correlating results. It would seem highly desirable, then, to carry out two such series of measurements on the same specimens and over this relatively wide spectral range.

This near infra-red spectral region is also worthy of study in this connection for reasons other than the mere fact that we are thereby enabled to check theory over a wider extent of wave-length than visual observations alone could accomplish. As is well recognized, optical phenomena in the ultra-violet and possibly throughout the visible spectrum are, in general, conditioned by electronic vibrations. For wave-lengths longer than about 3μ, on the other hand, we have ample evidence—e.g., molecular rotation spectra and certain absorption investigations—that the vibrators may be of atomic or molecular dimensions. The short infra-red may then be regarded as a sort of transition region in which we must look to experiment to indicate something as to the coupling of the short wave-length and long wave-length theory—a region accordingly in which investigation is particularly desirable.

One way in which we may seek to throw light on this question of size of vibrator is to calculate e/m for as wide a frequency range as possible by substituting observed values of rotation and dispersion in the above formula. Such a series has been calculated out to 2μ and will appear in the results.[11]

[11] Too much must not be expected from such calculation. As Professor Lorentz remarked to the writer in a recent conversation on this subject, no very definite conclusions can be based on the Becquerel type of formula when it breaks down. It is of interest, however, to note the general trend of results for the large variety of liquids tested, and one or two inferences may be safely drawn.

Experimental Details. A full account of the spectrobolometric method of measuring magnetic rotation has been given in previous papers by the writer[12] and need not be repeated here. The apparatus was practically the same as that formerly used, with the exception of the substitution of a small eight coil Thomson galvanometer (made in this laboratory) for the former four coil. It was carried on a special pier built on a massive concrete block cushioned on five sides with sawdust. The liquids were contained in a cell 9.54 mm thick with thin strain-free plate glass ends, whose rotation was, of course, measured and allowed for. This was located between the poles of the large electromagnet in a field of approximately 12050 gausses. A tungsten strip filament lamp (from the Nela Laboratory) served as source and gave sufficient energy to allow rotation measurements on the more transparent liquids for the region between .56μ and 2.3μ.

Satisfactory temperature control proved difficult and was not, indeed, entirely attained. The best results were obtained by water-jacketing the magnet pole pieces and by blowing a stream of chilled air at the cell. In this way the temperature could usually be kept within a degree of 23°C, which was the mean aimed at throughout this work. Tests indicated that the errors due to uncertainty in temperature were smaller than the unavoidable ones from other causes.

Visual measurements, by way of check, were made with a Lippich tri-field polariscope, using sodium light. In practically every case the point determined in this way fitted very closely indeed on the bolometric rotation dispersion curve.

The refractive index measurements were made by the method of double dispersion, using a small spectrometer and hollow prism, in connection with the large spectrometer—minus, of course, its polarization auxiliaries. Large scale plots were made of these indices and the dispersion was determined by drawing tangents to the curves.

Accuracy. In this matter the rotation measurements were an

[12] L. R. Ingersoll, Phil. Mag. (6) *11*, p. 41, 1906; *18*, p. 74, 1909. Phys. Rev. *23*, p. 489, 1906; (2) *9*, p. 257, 1917.

improvement over any previously made with this apparatus. One or two small and hitherto unsuspected sources of error were traced out and corrected. The runs were almost all made at night to secure the freedom from vibration so necessary in bolometric work. The results were plotted on large size section paper and the measurements listed here were taken from the smooth curve. As nearly as can be estimated the resultant accuracy of the rotation measurements is of the order of 1% through the middle of the spectral range, with a somewhat larger probable error at the ends where the available energy is small. Considering the difficulties involved this is considered quite satisfactory.

In view of the fact that the refractive index measurements were a somewhat secondary consideration the highest order of accuracy was not aimed at in them. In the few cases possible the values determined were compared with the infra-red indices determined by other observers. While the accordance in absolute values was not in all cases such as might be desired, the *slopes* of the curves, giving the dispersion, were in good agreement, and it is to be noted that for the purposes of this research the absolute value is secondary to the dispersion, which is the quantity entering into formulas of the type above noted. Moreover as regards formulas into which n enters directly the situation is equally good; for the probable error of n, measured in per cent would in any case be almost negligibly small.

Materials. As already noted these were divided into two classes—pure liquids and aqueous solutions of metallic salts. The liquids studied were chosen to give as great a variety as possible. They ranged from heptane with a density of only .68 and correspondingly low refractive index, to methylene iodide, the heaviest organic liquid known, with a density of 3.31 and refractive index over 1.7; from the chemically simple carbon bisulphide to α-monobromnapthalene. In most cases they were purified by redistillation, or otherwise, shortly before use, and for this service I am greatly indebted to several members of the Chemistry Department of this University, particularly to Professor F. Daniels.

The salts of the ferromagnetic metals used in the aqueous solutions were as pure as could be readily obtained. The solutions were in general very nearly saturated.

RESULTS

The results a e shown in the accompanying tables and curves. The tables give for a selected series of wave-lengths Verdet's constant R (rotation in minutes of arc for unit length in unit field), the refractive index n, and (Table 1 only) values of e/m calculated with the formula given above, in the form

$$e/m = \frac{6\times 10^{10}\pi R}{180\times 60}/\lambda\frac{dn}{d\lambda}$$

The complete series of values of rotation measurements can be taken from the curves—which, to make evident the law of dispersion are plotted with inverse squares of the wave-lengths as abscissas—, and the dispersion for the five wave-lengths listed may readily be found, if desired, by calculating backwards from R and e/m. Hence material is here available for a very extensive test of magnetic rotation theories.

The densities of all the liquids, with a few exceptions, were carefully measured at the chosen working temperature, viz., 23°C, with a calibrated specific gravity bottle. Exceptions are ethyl iodide and tin and titanium tetrachlorides, the densities of which were taken from tables. The percentages of salt in the solutions are by weight, the figures being taken from tables, with the aid of the density determinations. They checked satisfactorily with calculations based on weights. In the few cases where density determinations are lacking the solutions were what would ordinarily be called "saturated."

It will be found that, with one or two exceptions, the values of density, and of the rotation and refractive index at $.6\mu$ are in satisfactory agreement with such as can be drawn (by interpolation or extrapolation) from standard tables. Xylene does not show as good agreement as most of the other liquids in this particular. It was not of the highest purity, being mainly ortho- but with more than a trace of para- and meta-xylene.

DISCUSSION OF RESULTS

DISPERSION OF ROTATION IN PURE LIQUIDS

The first thing which strikes the attention in glancing at the curves of Figs. 1 to 3 is the rather remarkable way in which the rotation dispersion follows the simple law of proportionality to

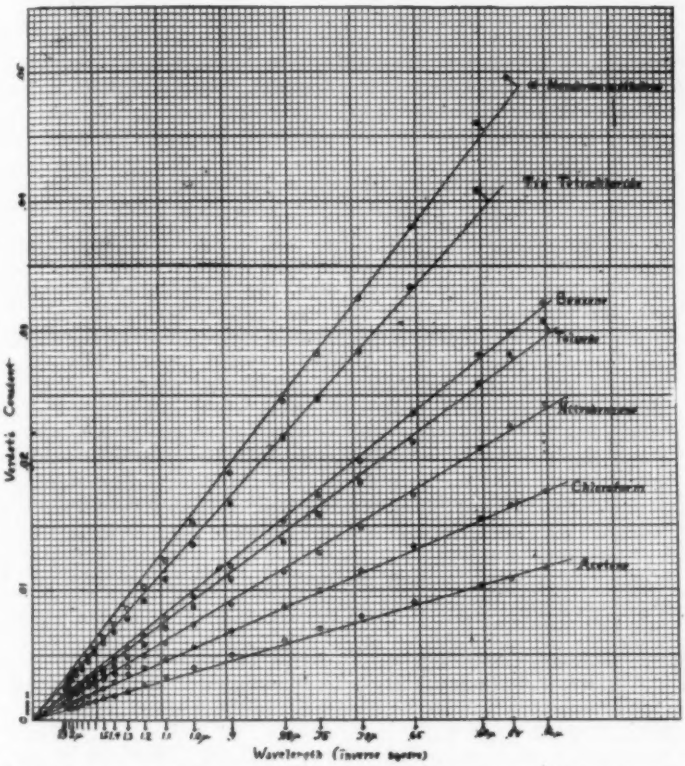


FIG. 1. Curves plotted with magnetic rotations as ordinates and inverse squares of the wave-lengths as abscissas. For convenience the actual wave-lengths in microns are indicated

the inverse square of the wave-length. For the alcohols, ether, chloroform and heptane the departure of the points from a straight line is not much greater than the probable experimental error. The other curves, however, with the exception of acetone,

TABLE 1.—*Summary of data for pure liquids at 23°C*

Liquid		Carbon Tetrachloride CCl_4	Tin Tetrachloride $SnCl_4$	Titanium Tetrachloride $TiCl_4$	Ether $C_4H_{10}O$	Chloroform $CHCl_3$	*n*- Heptane C_7H_{16}	Acetone C_3H_6O	Carbon Bisulphide CS_2	α-monobromnapthalene $C_{10}H_7Br$	Water H_2O
Density		1.583	2.22	1.74	.713	1.475	.681	.791	1.260	1.486	.997
$\lambda = .6\mu$	R	.0161	.0408	−.0131	.0102	.0155	.0119	.0103	.0394	.0460	.0126
	n	1.4599	1.5079	1.5951	1.3505	1.4425	1.3850	1.3569	1.6227	1.6558	1.3324
	$\frac{e}{m}\cdot 10^7$	.99	1.46	.....	.95	1.08	1.03	1.12	.72	.79	1.25
$\lambda = .8\mu$	R	.0089	.0217	−.0050	.0058	.0086	.0066	.0061	.0214	.0245	.0070
	n	1.4539	1.4993	1.5764	1.3465	1.4370	1.3811	1.3527	1.6031	1.6375	1.3280
	$\frac{e}{m}\cdot 10^7$	.96	1.79	.....	.88	1.01	1.13	.88	.80	.99	.80
$\lambda = 1.0\mu$	R	.0057	.0135	−.0026	.0036	.0056	.0043	.0040	.0135	.0152	.0044
	n	1.4509	1.4952	1.5689	1.3444	1.4343	1.3791	1.3506	1.5947	1.6296	1.3247
	$\frac{e}{m}\cdot 10^7$	.87	1.70	.....	.86	.94	1.03	.73	.75	.95	.50
$\lambda = 1.5\mu$	R	.0025	.0060	−.0010	.0016	.0024	.0018	.0017	.0058	.0063	*.0029
	n	1.4479	1.4911	1.5613	1.3419	1.4314	1.3768	1.3479	1.5858	1.6222	* 1.3210
	$\frac{e}{m}\cdot 10^7$	.76	1.16	.....	.36	.93	.56	.50	.65	.94	* .29
$\lambda = 2.0\mu$	R	.0013	.0031	−.0005	.0008	.0013	.0009	.0009	.0031	.0035	
	n	1.4463	1.4895	1.5585	1.3402	1.4301	1.3752	1.3464	1.5819	1.6192	* $\lambda = 1.25\ \mu$
	$\frac{e}{m}\cdot 10^7$	.38	1.48	.....	.11	.44	.15	.20	.39	.48	

TABLE 1 (continued)

Liquid		Methyl Alcohol CH_4O	Ethyl Alcohol C_2H_6O	*n*- Butyl Alcohol $C_4H_{10}O$	Benzene C_6H_6	Nitrobenzene $C_6H_5NO_2$	Toluene C_7H_8	Xylene C_8H_{10}	Ethyl Iodide C_2H_5I	Methyl Iodide CH_3I	Methylene Iodide CH_2I_2
Density		.790	.788	.807	.874	1.198	.863	.861	1.93	2.263	3.310
$\lambda = .6\mu$	R	.0093	.0111	.0120	.0281	.0209	.0258	.0232	.0279	.0318	.0476
	n	1.3285	1.3609	1.3992	1.4970	.....	1.4932	1.4933	1.5085	1.5262	1.7376
	$\frac{e}{m}\cdot 10^7$	.88	1.22	1.05	.99	.....	.97	1.09	1.13	1.15	.73
$\lambda = .8\mu$	R	.0051	.0060	.0067	.0153	.0114	.0137	.0128	.0151	.0178	.0268
	n	1.3245	1.3566	1.3950	1.4869	1.5355	1.4839	1.4842	1.4994	1.5157	1.7164
	$\frac{e}{m}\cdot 10^7$	.80	.85	.94	1.02	.59	.97	.87	1.15	1.12	.99
$\lambda = 1.0\mu$	R	.0032	.0038	.0043	.0095	.0073	.0087	.0080	.0097	.0112	.0169
	n	1.3222	1.3542	1.3928	1.4823	1.5295	1.4796	1.4799	1.4947	1.5108	1.7073
	$\frac{e}{m}\cdot 10^7$	.56	.70	.90	1.00	.60	1.17	.97	.95	1.13	.95
$\lambda = 1.5\mu$	R	.0019	.0019	.0018	.0039	.0031	.0035	.0035	.0041	.0048	.0073
	n	1.3180	1.3506	1.3896	1.4774	1.5234	1.4751	1.4757	1.4901	1.5064	1.6987
	$\frac{e}{m}\cdot 10^7$	.25	.29	.32	.88	.50	.67	.71	.84	1.10	.88
$\lambda = 2.0\mu$	R	.0013	.0010	.0014	.0022	.0018	.0020	.0019	.0024	.0027	.0040
	n	1.3135	1.3470	.....	1.4756	1.5204	1.4734	1.4737	1.4880	1.5043	1.6956
	$\frac{e}{m}\cdot 10^7$	.12	.12	.....	.43	.30	.29	.35	.35	.49	.73

show a distinct tendency to fall below the straight line for the middle part of the spectral region investigated and to rise at the short wave-length end. Toluene and carbon bisulphide are good examples.

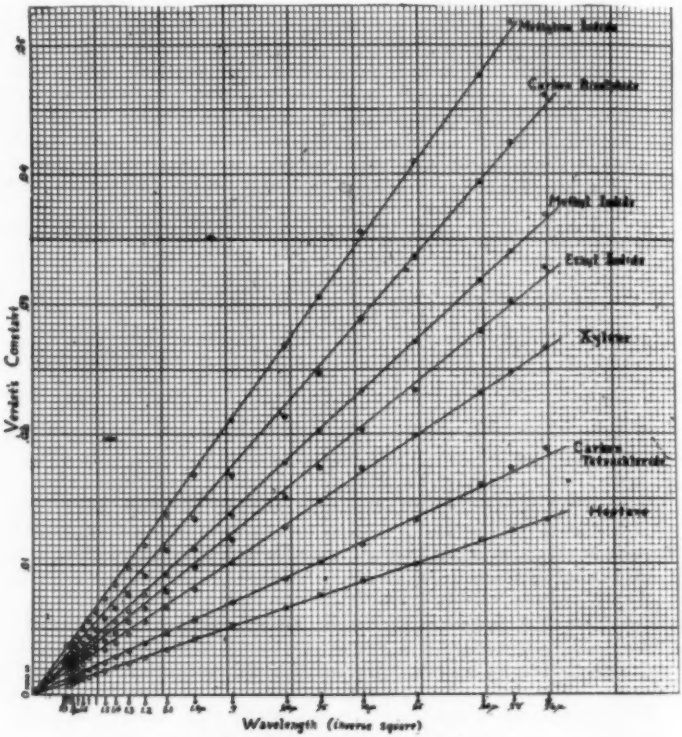


FIG. 2. For explanation see Fig. 1

Rotation Formulas. Of the many rotation dispersion formulas we shall discuss in connection with these curves only three, viz.,

$$\phi = n\left\{\frac{a}{\lambda^2}+\frac{b}{\lambda^2-\lambda_1^2}+\frac{c}{\lambda^2-\lambda_2^2}\right\} \tag{1}$$

$$\phi = \frac{1}{n}\left\{\frac{a'}{\lambda^2}+\frac{b'\lambda^2}{(\lambda^2-\lambda_1^2)^2}+\frac{c'\lambda^2}{(\lambda^2-\lambda_2^2)^2}\right\} \tag{2}$$

$$\phi = K\lambda dn/d\lambda \tag{3}$$

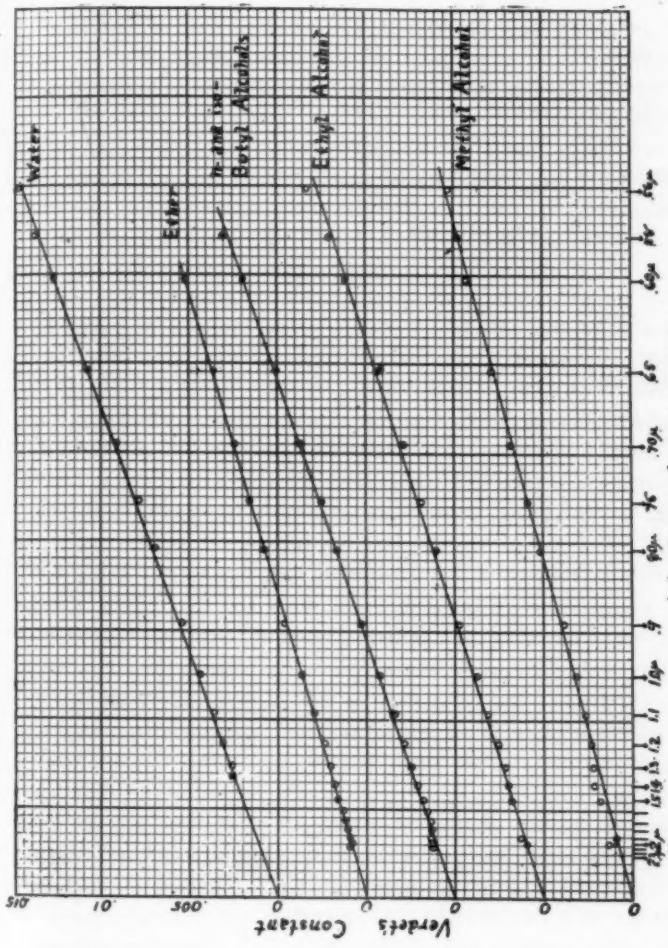


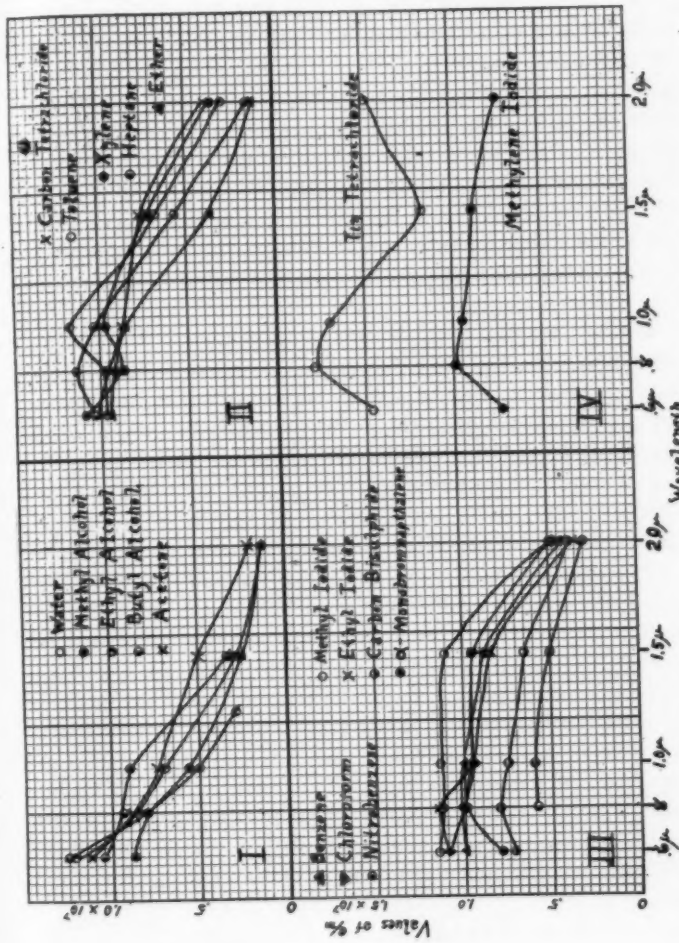
FIG. 3. For explanation see Fig. 1

The first two are based on what might be termed the older magneto-optic theory and are simple extensions—by the addition of a third term—of those derived by Drude (Lehrbuch d. Optik) on the hypothesis of molecular currents, and of the Hall effect, respectively. λ_1 is the wave-length of an ultra-violet absorption line and λ_2 of an infra-red.

Now a little study of these formulas will make it apparent that, except for the long wave-length end, the three constants (five if we do not specify λ_1, and λ_2) could be chosen so that either formula would fit the observed curves—save for acetone—very well. This is not true, however, for the longer wave-lengths. As we approach, from the short wave-length side, an infra-red absorption band, that is, one—if there be such—which affects the magnetic rotation, formula (1) calls for a *decrease* of rotation. Similarly the Hall effect formula predicts an *increase*—it being assumed in both cases that the constants c and c' are positive. While in most cases the rotation dispersion shows a slight upward tendency on the long wave-length end, calling for the second formula, there are one or two liquids, notably tin tetrachloride, where the reverse is true.

It may be remarked, however, that it is not safe to place too much dependence on these measurements for the two or three longest wave-lengths. While a great deal of effort was expended to make them as accurate as possible the experimental difficulties were very great. The same may be said of determinations in the absorption region in the neighborhood of 1.7μ shown by many of the hydrocarbons. The conclusion we can safely draw—based on the fact that the departure from the straight line (inverse square law) on the long wave-length end is of the order of the experimental error—is that, in the region investigated the effect, on the rotation, of infra-red bands is *small*. There is no observable effect traceable to the 1.7μ absorption region in any case.

Becquerel Formula. Calculation of e/m. As already mentioned the more modern point of view in magneto-optic rotation theory leads to a formula of the type of (3) and this has been applied to the substances listed in Figs. 1–3. The results are given in


Carbon Tetrachloride
Toluene
Xylene
Heptane
Ether
Iso Tetrachloride
Methylene Iodide
Water
Methyl Alcohol
Ethyl Alcohol
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Acetone
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Ethyl Iodide
Carbon Bisulphide
Monobromnaphtalene
Benzene
Chloroform
Nitrobenzene
II
IV
I
III
Values of ℘
Wavelength
2.0μ
1.5μ
1.0μ
.5μ
0
.5
1.0
1.5 x 10⁷
1.0 x 10⁷

FIG. 4.

Table 1 and Fig. 4 not, however, as a comparison of observed and computed rotations, but by reversing the formula as previously explained and calculating e/m. In this way we are led—subject to the reservations already mentioned in the footnote—to some interesting conclusions as to the size of vibrator. When e/m shows a reasonably constant value (i.e. the Becquerel formula is obeyed) of the same order of magnitude as that found in other ways, as shown by tin tetrachloride and methylene iodide, we may assume that the vibrators are electronic in size. When, however, as in water and the alcohols, e/m decreases rapidly with longer wave-length we infer that the proportion of atomic vibrators is making itself felt. A *discontinuous* change from electronic e/m to atomic e/m is, of course, not to be expected.

It may be remarked that, in view of the fact that these liquids all obey substantially the same law of rotation dispersion the marked changes in the e/m curves between the four types are largely due to differences in the ordinary dispersion curves. This means that certain infra-red bands which are influencing the refractive index curves *have no effect* on the magnetic rotation.

Solutions. The results on solutions are shown in Fig. 5 and Table 2. It will be seen that the inverse square law also holds here in a general way, but not as well as for pure liquids. The spectral range is also considerably shortened by the fact that the absorption of water prevents measurement for wave-lengths longer than about 1.35μ. Considerable effort was spent in calculating corrections for the effect of the solvent (water) in an attempt to secure results characteristic of the salts alone. The curves obtained were in many cases most irregular and hardly justify reproduction. In general it may be said, however, that where the salt solution shows a smaller rotation than that of water (curve below the dash line) the salt itself may be considered to show a negative rotation, but there may be exceptions to this statement.

Thoulet's solution ($2KI+HgI_2+aq$) is of interest as showing one of the highest known rotations. As used it had a density of only 2.45 and this could be increased by concentration with doubtless a corresponding increase in its Verdet constant.

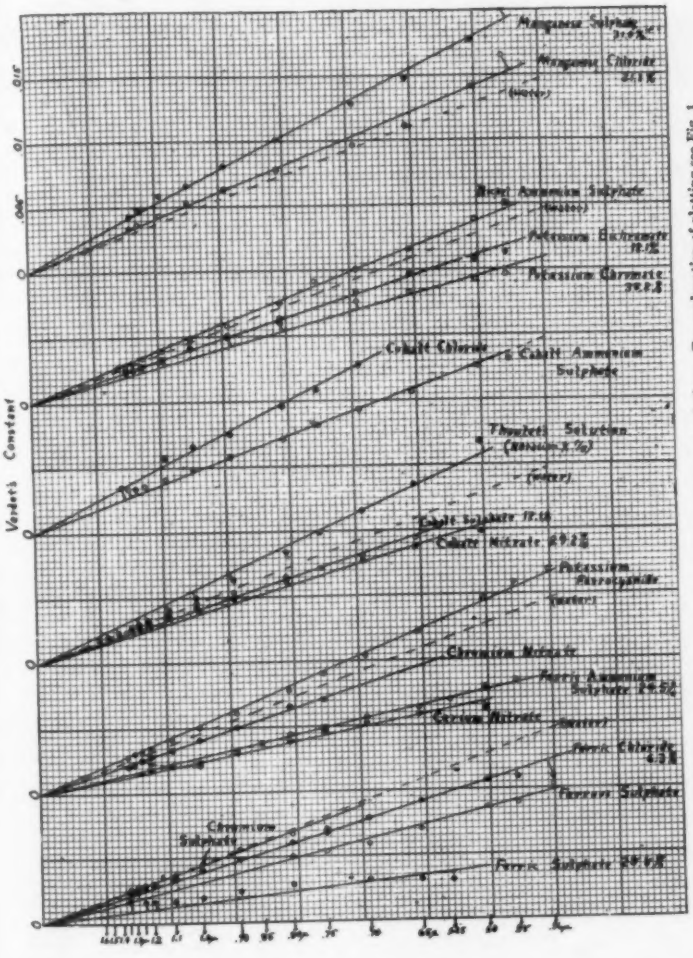


FIG. 5. Rotation curves for concentrated aqueous solutions. For explanation of plotting see Fig. 1

In a previous research the writer[13] found that films of iron showed a magnetic rotation which increased out to a wave-length of 1.5μ and then stayed nearly constant to 2μ. The fact that only the slightest trace of such behavior is exhibited by iron salt solutions is a bit of evidence for this particular phenomenon of magnetism being regarded as molecular rather than atomic in character.

A series of e/m calculations was also carried out for these solutions. In general the values fall off rapidly with increasing wave-length, as in the case of pure water.

Negatively Rotating Liquids. Our previous discussion has been entirely on positively rotating liquids. Fig. 6 shows the measurements on the three negatively rotating liquids tested, viz., strong solutions of ferric chloride and potassium ferricyanide, and the

TABLE 2.—*Summary of data for aqueous solutions at 23°C*

		Ferric Chloride (1)	Ferric Chloride (2)	Potassium Ferricyanide	Potassium Ferrocyanide	Ferric Sulphate	Ferrous Sulphate	Ferric Ammonium Sulphate	Cobalt Sulphate	Cobalt Chloride	Cobalt Nitrate
Density		1.523	1.049	1.187	.....	1.446	.....	1.250	1.322	1.296	1.308
%		47.8	6.3	31.4	.....	.....	.....	24.5	.....	.....	29.2
$\lambda = .6\mu$	R	.....	.0107	−.0233	.0147	.....	.0087	.0078	.....	.....	.0099
	n	.....	1.3487	1.3878	.....	1.4234	.....	1.3881	.....	.....	1.3892
$\lambda = .8\mu$	R	−.0399	.0061	−.0056	.0078	.0029	.0050	.0044	.0065	.0096	.0060
	n	1.4941	1.3442	1.3810	.....	1.4160	.....	1.3817	1.3816	1.3985	1.3835
$\lambda = 1.0\mu$	R	.0215	.0040	−.0017	.0051	.0020	.....	.0021	.0046	.0066	.0043
	n	1.4860	1.3407	1.3768	.....	1.4113	.....	1.3779	1.3778	1.3945	1.3796
$\lambda = 1.25\mu$	R	−.0110	.0026	−.0001	.0032	.0016	.....	.0026	.....	.....	.0029
	n	1.4803	1.3366	1.3731	.....	1.4061	.....	1.3730	.....	.....	.....

[13] Phil. Mag. (6) *18*, p. 74; 1909.

TABLE 2.—(Continued)

		Cobalt Ammonium Sulphate	Nickel Ammonium Sulphate	Cerium Nitrate	Manganese Chloride	Manganese Sulphate	Chromium Nitrate	Chromium Sulphate	Potassium Chromate	Potassium Bichromate	Thoulet's Solution
Density		1.106	1.054	1.202	1.326	1.369	1.087	1.140	1.372	1.085	2.445
%		.....	.....	.....	31.3	31.0	.....	.....	38.2	12.1	.....
$\lambda = .6\mu$	R	.0126	.0139	.0062	.0141	.0178	.....	.....	.0092	.0108	.0841
	n	1.3552	1.3438	1.3650	.....	1.3948	.....	.....	1.4276	1.3540	.....
$\lambda = .8\mu$	R	.0071	.0075	.0039	.0078	.0101	.0066	.0067	.0060	.0064	.0422
	n	1.3505	1.3397	1.3594	1.4069	1.3896	1.3468	1.3553	1.4180	1.3487	1.5685
$\lambda = 1.0\mu$	R	.0049	.0048	.0024	.0054	.0066	.0041	.0045	.0041	.0042	.0249
	n	1.3470	1.3362	1.3460	1.4030	1.3857	1.3431	1.3514	1.4127	1.3447	1.5590
$\lambda = 1.25\mu$	R	.0035	.0030	.0016	.0034	.0043	.0025	.0028	.0026	.0025	.0152
	n	1.3432	1.3324	1.3419	1.3987	1.3811	1.3391	1.3472	1.4079	1.3407	1.5525

fuming liquid titanium tetrachloride. This last is of interest in that it is the only known diamagnetic substance showing negative rotation.

As already mentioned several investigators, notably Siertsema[14] have concluded on the basis of visible spectrum measurements that the rotation dispersion of such substances is much greater than in positively rotating liquids, being more nearly proportional to the inverse fourth power of the wave-length. Now the curves of Fig. 6 show that over this wider spectral region both titanium tetrachloride and the strong ferric chloride solution obey fairly closely an *inverse cube law*. Potassium ferricyanide, on the other hand, shows a much greater dispersion than this—greater even than the inverse fourth power.[15]

[14] Amst. Proc. *18*, p. 925; 1916.

[15] Cf. Siertsema, Arch. Neer. (2) *5*, 447, 1900.

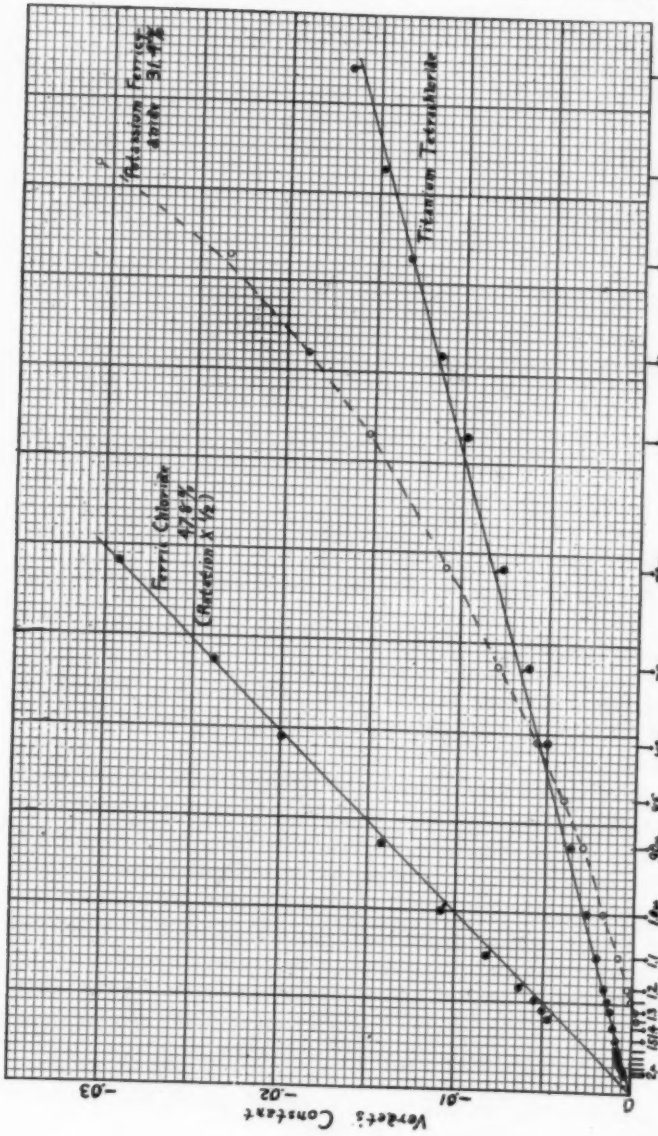


FIG. 6. Curves for negatively rotating liquids. For explanation of plotting see Fig. 1

Other details. A carbon bisulphide solution of iodine gave rotation and refractive index measurements almost the same as the pure solvent. The rotation curve for colloidal iron oxide in water could not be definitely distinguished from that for pure water. Similarly *n.*- and iso-butyl alcohols gave practically identical curves.

Two solutions of nickel salts, viz., the nitrate and chloride, were tested but were found to absorb too strongly for measurement save in relatively narrow transmission bands at $.8\mu$ and $.9\mu$, respectively. Incidentally it may be remarked that these salts in concentrated solution would constitute admirable filters if it was desired to utilize only this portion of the infra-red.

In conclusion I am glad to acknowledge my indebtedness to the Rumford and American Association funds for grants; to members of the Chemistry Department, as already mentioned, for their kindness in preparing pure liquids; and to Professor H. A. Lorentz, who, on the occasion of his recent visit to this laboratory, was good enough to give the writer the benefit of his criticism. I should like also to express my appreciation of the work of my assistant Mr. N. G. E. Sharp, who made all of the observations with painstaking care.

SUMMARY

1. The magnetic rotation and refractive index of twenty pure liquids and as many aqueous-solutions of metallic salts have been measured for the spectrum range between $.56\mu$ and 2.3μ.

2. Positively rotating liquids show a rotation very nearly proportional, in most cases, to the inverse square of the wave-length, indicating that infra-red absorption bands have small influence on the rotation in this region.

3. The few negatively rotating liquids show a much greater rotation dispersion. This is nearly the inverse cube for titanium tetrachloride and concentrated ferric chloride solution, while for potassium ferricyanide solution it is almost as the inverse fifth power of the wave-length.

4. Values of e/m calculated from these measurements on positive liquids show in general a diminution for longer wave-length, as might be expected. Several types of curves may be distinguished in this connection.

PHYSICAL LABORATORY,
UNIVERSITY OF WISCONSIN.
JULY 12, 1922.

INSTRUMENT SECTION

THE CLASSIFICATION OF OPTICAL INSTRUMENTS

By T. Smith

ABSTRACT

Exception is taken to the classification of optical instruments by the signs of their powers, and an alternative division comprising five classes is proposed, based upon the separation of the four Gaussian constants into two groups according to their signs. This classification cannot be modified by the addition to the system of inverting prisms and the like, and the properties usually associated with the sign of the lens in reality depend upon its class according to the new system. Each class may have systems of positive or of negative power.

The elementary theory of optical instruments which we owe to Gauss has the great merit that attention may be given wholly to the events which take place in the object space and the image space, the method by which the rays are altered in direction and position, and even the position of the instrument which causes these changes, being unimportant. This treatment is highly advantageous when the purpose is to consider the general correlation between incident and emergent rays, but in the practical applications of the theory to the construction and use of real instruments the position of the instrument is of the greatest importance. This would be rendered more apparent if it became customary at a later stage of the theory to consider the position of the instrument in relation to the cardinal points; such a development leads naturally to a classification of instruments in which there are five groups, important special cases such as telescopes being regarded as borderline cases or as members of two groups. The division proposed is more fundamental than the usual separation of lens systems into positive and negative combinations, a distinction which is not generally correct as regards many of the properties usually associated with them.

The properties of a system, including the positions of the extreme surfaces relative to the cardinal points, are given by the four Gaussian constants A, B, C, D,[1] which satisfy the identity $BC-AD=1$. The ordinary division depends wholly on the sign of A, the power of the system. The essential theoretical distinction between positive and negative lenses is indicated in Figs. 1 and 2 by means of three incident parallel rays identified by the letters P, Q, R: the position of the instrument is immaterial and both object space and image space are supposed to extend to

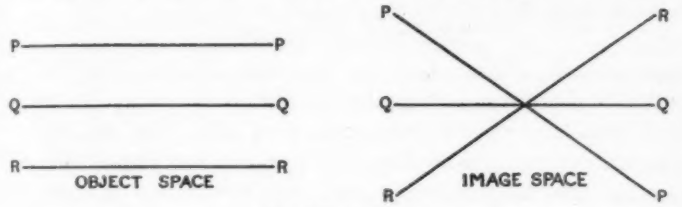


Fig. 1. Positive Lens.

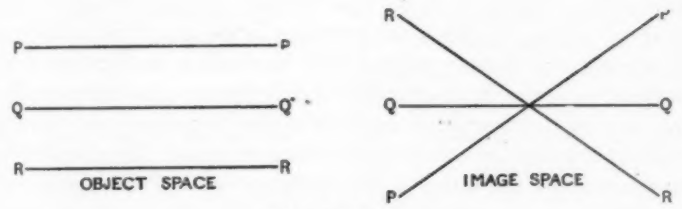


Fig. 2. Negative Lens.

infinity in every direction. In the classification now proposed the basis is the grouping of the constants according to agreements or disagreements of sign. Let the constants of one sign be included in one bracket, and those of another sign in another bracket. There are then six possible groups
$[ABCD]$, $[ABC]$ $[D]$, $[A]$ $[BCD]$, $[AB]$ $[CD]$, $[AC]$ $[BD]$, $[AD]$ $[BC]$, it being of no consequence which bracket of a pair corresponds to

[1] These constants A, B, C, D are respectively $s_{1,n}$, $\frac{\partial s_{1,n}}{\partial s_1}$, $\frac{\partial s_{1,n}}{\partial s_n}$, $\frac{\partial^2 s_{1,n}}{\partial s_1 \partial s_n}$ in the notation used in calculations.

a positive and which to a negative sign. An algebraically exhaustive list would include the groups $[ABD]\,]C]$ and $[ACD]\,[B]$, but these must be excluded since they require $BC-AD$ to be negative. The actual number of classes is one less than the number of these groups, for if a system is considered in the reverse direction B and C are interchanged. It follows that the two groups $[AB]\,[CD]$ and $[AC]\,[BD]$ correspond to a single class of instrument.

The positions of pairs of conjugate points on the axis are given in terms of A, B, C, D, by the relation

$$Axx'-Bx'-Cx+D=0, \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where x is the distance from the first surface to the object point, and x' is the distance from the last surface to the image point, both considered positive when measured away from the system into the surrounding medium. It is at once evident from this equation that the positions of conjugate points depend upon the ratios of these constants, and that their relative signs rather than their absolute signs are important. The particular property affected by a change of all the signs without a change of magnitude of these four quantities is the inversion of the image of an object occupying a particular position, but in modern instruments the designer need pay little attention to this feature of a system as he has several devices which he may adopt to modify this result without altering the values of the four constants. The properties represented by the ratios of the constants on the other hand are fundamental and cannot be influenced by such devices as the introduction of reflecting surfaces.

From the equation connecting x and x' it is easy to see what properties are associated with each of the groups that have been described. Suppose that F (Figs. 3 to 8) is the point at which incident parallel rays are brought to a focus, that U is the image of the vertex of the first surface in the system, and that V is the vertex of the last surface. Then F, U, V are three points on the axis in the image space of which V is necessarily real while F and U are only real if they are encountered by a wave which has traversed the system after it has passed through V. There are six cases to consider. For U may be encountered by the wave

before it reaches F or after it has passed through F, and V in either case may precede both, fall between or follow both U and F. If the points are placed in the order in which they are met by the wave, the following correspondences may be derived at once from equation (1):

$$VUF=[ABCD], \qquad VFU=[AC]\,[BD],$$
$$UVF=[ABC]\,[D], \qquad FVU=[A]\,[BCD],$$
$$UFV=[AB]\,[CD], \qquad FUV=[AD]\,[BC].$$

The general properties of members of any class may be inferred either from equation (1) or from the order of the letters F, U, V if it is remembered that the image of the real part of the object space axis extends from F in the positive direction (through infinity if necessary) to U. Either method shows that in every group with the exception of the last, $[AD]\,[BC]$, there is a range of the axis in which a real image of a real object may be formed. The portion of the image axis which corresponds to the real object space axis is indicated by a thicker line in the image.

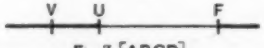


Fig. 3. [ABCD]

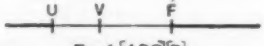


Fig. 4. [ABC][D]

Fig. 5. [AB][CD]

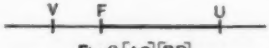


Fig. 6. [AC][BD]

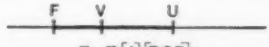


Fig. 7. [A][BCD]

Fig. 8. [AD][BC]

Among the special cases it will be noted that thin lenses, which have $B=C=1$ and $D=0$, are members, if the power is positive, of groups $[ABCD]$ and $[ABC]\,[D]$; if the power is negative they belong to groups $[A]\,[BCD]$ and $[AD]\,[BC]$. When the thickness are small without being exactly zero the groups are those mentioned second in each case. It is because the negative lenses ordinarily used belong to the class $[AD]\,[BC]$, and not because the power is negative, that all the images they form are virtual.

It is not difficult to construct positive combinations which have this property.

Other special classes comprise the telescopes. For instance, prismatic binoculars, gun-sighting telescopes and astronomical telescopes belong to either $[ABCD]$ or $[A]$ $[BCD]$. On the other hand, Galilean binoculars belong to $[ABC]$ $[D]$ or $[AD]$ $[BC]$, and their undesirable properties are wholly attributable to the class to which they belong and have no connection with the erectness of the images they yield.

The adoption of this classification will lead naturally from the Gaussian treatment of rays to the consideration of entrance and exit pupils, an important branch of geometrical optics which has not until lately, in this country at all events, received a proper amount of attention. It would be convenient to have short descriptive titles for each group, but the writer wished to have the opportunity of hearing the views of other workers before making any proposals of this kind.

EDITORIAL NOTE

The above paper on "The Classification of Optical Instruments" was read by the author before the Optical Society of London, June 8, 1922. It is published here by arrangement between the Optical Society of London and the Optical Society of America, in hopes that the author's proposal will have as wide discussion as possible.

For the benefit of such readers as may perhaps not be familiar with Mr. Smith's other optical writings, it may be well to state that "the four Gaussian constants A, B, C, D" which he employs have the following meanings (as he explains also in a footnote):

A denotes the refracting power of the system, usually denoted in this Journal by F or $F_{1,\,m}$, if the system is supposed to consist of m refracting surfaces; (however, Mr. Smith uses α instead of F and n instead of m.)

$B=\dfrac{\partial A}{\partial F_1}$, where F_1 denotes the refracting power of the first surface;

$C=\dfrac{\partial A}{\partial F_m}$, where F_m denotes the refracting power of the mth surface;

$D=\dfrac{\partial^2 A}{\partial F_1 \partial F_m}=\dfrac{BC-1}{A}$.

Now if the vertices of the first and last surfaces are designated by A_1 and A_m, respectively, it may be shown (*cf. J.O.S.A.*, IV, pp. 246, 247; 1920) that the positions of the focal points, (F, F') are defined by the simple relations:

$$A_1F=-\frac{B}{A}, \quad A_mF'=\frac{C}{A}.$$

If M, M′ designate the positions of a pair of conjugate points on the optic axis, the symbols x, x' employed by Mr. Smith may be defined as follows: $x=MA_1$, $x'=A_\infty M'$. Assuming that the optical system is surrounded by air on both sides, and employing the Newtonian abscissa-equation, we derive immediately the relation:

$$\left(\frac{B}{A}-x\right)\left(x'-\frac{C}{A}\right)=-\frac{1}{A^2},$$

which, by virtue of the relation $BC-AD=1$, reduces to the equation given by Mr. Smith, namely:

$$Axx'-Bx'-Cx+D=0.$$

For the three points which Mr. Smith calls F, U and V, it follows that

$$VF=\frac{C}{A},\quad VU=\frac{D}{B},\quad UF=\frac{1}{A\cdot B}.$$

The five classifications above are evident from these relations.

J. P. C. S.

SUMMARY OF THE LITERATURE RELATIVE TO THE FORMATION OF FILM ON POLISHED GLASS SURFACES

By George W. Morey

The stability of polished glass surfaces is of prime importance in the design and manufacture of optical instruments, and all factors affecting their stability are worthy of careful consideration. Some glasses are inherently inferior in their resistance to the corrosive action of water and weak acids, and such glasses are to be avoided whenever possible. Experience has shown the relative reliability of different glass types and glass compositions, and tests have been devised which enable the optician to avoid actually inferior types.[1] But glasses possessing a high degree of resistance to such "weathering" action often give trouble by becoming covered with a coating resembling that produced by the weathering of an inferior glass, but actually due to entirely different causes. This particular type of coating has been called "film," and the following report summarizes the information contained in the literature on the formation, appearance, cause, and prevention of "film" on polished glass surfaces.

The phenomenon in question is thus described by Ryland:[2] "In every type of enclosed optical instrument, instances, more or less numerous, of film will be found. By film is meant the coating of lens and prism surfaces with what is apparently a thin deposit of moisture. This has caused much trouble and annoyance, many instruments being rendered quite useless until taken apart and cleaned. The film appears to have several characteristics. It apparently consists of a series of globules of moisture, forming patterns on the surface similar to those made by cleaning with a linen rag which has seen much service. Often a series of larger globules will occur, each surrounded by a clear space.

[1] G. W. Morey, J. Soc., Glass Technology, *6*, p. 20–30; 1922.
[2] H. S. Ryland, Trans. Opt. Soc., *19*, p. 178–83; 1918–19.

Parts of a surface under pressure from mounts will be clear for a small space surrounding the points of contact, the clear space being fringed by a denser deposit. Prisms will often show a distinct pattern of the seat, the part covered by metal having a fairly dense deposit, a fairly clear space occurring where the surface is free, becoming again more dense away from the metal. A cut, scratch or hole in the surface is generally surrounded by a clear space, beyond which the deposit is again more dense.

"If a drop of water from a pipette is allowed to run over a filmed surface, it will leave a track which is quite free from any trace of scum. Microscopic examination shows no injury to the surface after filming. Instruments such as telescopes, in which the air is occasionally changed, very seldom film. When they do it is generally the case that they have been out of service for some time."

The above description of filming agrees well with that of other writers. That, even in cases in which the film appears uniform to the unaided eye, it actually consists of tiny discrete drops, is stated by Ryland (loc. cit., p. 183) and by Jones.[3] The tendency of film to form on reticules ("graticules") and similar etched surfaces is often mentioned;[4] an excellent photomicrograph of such a deposit in a reticule from a prism binocular is given by Martin and Griffith.[5] That such deposits are usually found in instruments which after assembly are made air and water tight as opposed to those in which there is opportunity for circulation of air is brought out by Jones, by Ryland and by Beck. The latter also states that "The Admiralty informed him that they have never met with it (film) inside submarine periscopes which are hermetically sealed and filled with dry air. He was told that it had not been met with in the Aldis unit sight when properly sealed, except in some experimental cases when a coating of

[3] Remarks on the filming of glass. By H. S. Jones of the Inspection Dept., D. I. O. S. Report submitted by Lt. Col. A. C. Williams, Dept. of Scientific and Industrial Research, Standing Committee on Glass and Optical Instruments.

[4] Discussion on the filming of glass held by the British Optical Instrument and Manufacturers Association.

[5] L. C. Martins and C. H. Griffiths. Trans. Opt. Soc. London, *20*, p. 135–54; 1920.

glycerine had been placed on the internal surfaces to pick up floating dust particles." Martin and Griffiths state that film is most often found in reticules, next in field lenses of eye pieces, next in prisms.

It follows from the above that in enclosed optical instruments a deposit, consisting of more or less discrete drops, tends to form on the glass surfaces, most especially on reticules. It also follows, e.g., from the data furnished by Beck, that such film is not met with even in enclosed instruments, when such instruments are assembled with great care, as is the case with periscopes. The important conclusion that the film is not a permanent attack of the glass surface, but on the contrary the original surface appears unchanged even when examined under the microscope after washing off the film with distilled water, is confirmed by Martin and Griffiths. The latter report: "As far, at least, as the globular deposit is concerned, the surface of the glass shows no trace of corrosion, when examined under the microscope, after the deposit of film has been washed off."

The cause of film has not yet been established. Two factors, however, seem to be necessary; the presence of water (moisture) and the presence of dirt or grease, especially the latter. French,[6] Chalmers,[7] and Wright[8] emphasize this point. Ryland writes, "A number of experiments have been tried in order to determine the cause of film. Certain types of black, notably the japan black and those containing pitch or bitumen, almost always cause film; aluminum machined and not cleaned afterwards; a small trace of animal matter or beeswax in the closed space will give trouble." Martin and Griffiths state that "moisture alone has no affect in producing the globular deposit" and that "the presence of lubricants does not produce globular deposit nor disintegration of surfaces unless moisture is present." The consensus of opinion is that, irrespective of the stability of the glass, elimination of dirt, grease and moisture are essential to the prevention of film.

[6] See discussion of the paper by Ryland, loc. cit.

[7] See discussion of the paper by Martin and Griffiths, loc. cit.

[8] "The Manufacture of Optical Glass and of Optical Systems," Lieut. Col. F. E. Wright. Ordnance Dept. Document No. 2037.

Ryland, after outlining precautions to be taken in cleaning, writes, "The use of these precautions will apparently make even poor glass remain free from film." French, Beck, Chalmers, Jones and Wright all agree as to the imperative necessity of meticulous cleanliness in assembly. Jones states that, "Generally speaking, it may be said that those firms who had taken the greatest care with the cleaning to ensure absolute cleanliness had the least trouble with film, whilst those who had taken fewest precautions to ensure cleanliness had most trouble." He also cites this case: "One firm who have had very considerable trouble from film, noticed that not a single instrument in which lenses etc. had been cleaned by the foreman of the assembly department had been rejected for film, and that the ordinary cleaning methods were used, i.e., without special precautions."

The nature of the glass, however, is probably not without importance. While Ryland asserts that proper precautions will prevent film on even poor glass, he states that "Different glasses however appear to have different susceptibility to film; the most troublesome glass I have found to be one made of borosilicate crown." In the discussion on filming held by the British Optical Instrument Manufacturers Association, it was brought out that "generally speaking, glasses showing the greatest affinity for water give the most trouble," though in this connection it should be noted that borosilicate crown, designated by Ryland as the most troublesome, is not especially susceptible to weathering. In addition to laying stress on cleanliness in assembly it is stated that "Care should be taken in the choice of glass. Hygroscopic glasses are to be avoided." Martin and Griffiths in a series of experiments on the formation of film, were unable to detect any difference between ordinary crown and light flint. On the other hand they state that no film had ever been observed on reticules made by a certain German firm, who used a light barium flint, Jena O 463. The evidence collected by Jones on this point is mainly negative, with the exception of an instance cited in which, "One firm had a lot of trouble with the graticulated discs of prismatic binoculars owing to the formation of globular deposits. This has been entirely overcome by simply changing from plate

glass to baryta light flint, without alteration of methods of cleaning." This latter case is probably one in which an actually poor glass had been used, as opposed to the majority of cases in which film was formed on fairly resistant glass, as a result of careless cleaning. It shows the necessity of choosing a good type of glass for the manufacture of such parts as reticules, though the light barium flint is probably not superior to many other glasses in common use.

Following are the precautions enumerated by Ryland as a complete preventative of filming:

1. No japan or bitumen black to be used on interior surfaces.
2. No pitch or beeswax to be used within the case.
3. All interior surfaces must be thoroughly cleaned and free from all animal matter such as finger marks. In the case of aluminum or other porus metal, heat treatment is necessary after machining to remove all trace of grease.
4. The lenses and prisms after ordinary cleaning to be dipped in hot running water with a pair of tweezers and wiped dry with clean linen (see 5 and 7) without being touched by the fingers again.
5. After washing the linen used for cleaning purposes, it must be well rinsed in hot water until all trace of soap is gone.
6. Dust must be removed with a clean camels hair brush and not by blowing.
7. The linen used for cleaning must be used in such a way that no part of it which has been touched by the fingers is brought into contact with the lens or prism surfaces.
8. All surfaces must be well polished and free from "orange peel" effect. If the pitch polisher leaves a trace of scum, a small quantity of glacial acetic acid added to the pitch when melted will prevent it."

While all writers do not agree that the above precautions will absolutely prevent film (Martin and Griffiths, Beck) there seems to be no doubt as to their being efficacious in most cases. In regard to the individual precautions, in some cases japan or bitumen do not appear to be at fault: "The black used by some American firms has not been found to be satisfactory in some instances,

and improvement had resulted in the use of a black with a reliable composition" (Jones). That precaution No. 3 is essential appears to be without dispute. Precaution No. 4, dipping lenses, after ordinary cleaning, is recommended by Martin and Griffiths, whose experiments show clearly its efficiency.

From the facts enumerated, the following conclusions can be drawn with some degree of assurance.

1. Filming, i.e., the formation of more or less isolated drops on the polished surfaces of glass instruments, is a result of the deposition of water contaminated by greasy matter.

2. Both water and grease are essential to the formation of film, and hence the utmost care must be taken to thoroughly clean the glass surfaces themselves, to ensure that no moisture or grease, or material which may yield moisture or grease, is contained in the space within which the glass surfaces are confined.

3. The glass should be of good quality, at least as good as Class 3 as determined by the iodeosine test.

GEOPHYSICAL LABORATORY,
CARNEGIE INSTITUTION OF WASHINGTON,
JULY, 1922.

A SUSPENSION TO ELIMINATE MECHANICAL DISTURBANCES

By Albert P. Carman

The writer recently was stopped for weeks in an investigation by troublesome vibrations due to various causes, but principally to the passing of heavy motor trucks. The laboratory is a brick building with very heavy masonry walls and with numerous masonry cross walls, and delicate instruments are not in general disturbed by mechanical disturbance even in the upper stories, but heavy motor trucks rolling over neighboring brick pavements with their concrete foundations shake the earth for considerable distances and with it the whole building. These earth vibrations seem to be particularly troublesome in the basement. Numbers of devices were tried to eliminate the vibrations, including a modified Julius suspension, but without success. Finally attention was called to a paper by Airy (Royal Astron. Society Monthly Notices, *17*, p. 160; 1856), which has suggested the solution which we have worked out for our difficulty. Airy devised a support for the mercury vessel of the reflex-zenith tube at Greenwich Observatory, using a series of platforms suspended by broad bands of vulcanized caoutchone, platform number one, carrying the mercury vessel, being suspended from supports carried on platform number two, and this being in turn suspended from supports carried on platform number three. Fig. 1 shows our scheme. A series of triangular wooden boxes, *A*, *B*, and *C*, were loaded with scrap lead. Box *A* was suspended from a rigid support resting on the concrete floor by three fine piano wires *DDD;* the box *B* was suspended from supports on *A* by pure gum tubing *EEE;* and the box on platform *C* was suspended from supports erected on *B* by another size and length of pure gum tubing *FFF*. The platforms were also connected at a number of points by small rubber bands hooked over tacks, so as to dampen quickly swaying motions. On each piano wire, there was a cylindrical weight of about 500 grams that could be clamped at any desired

point on the wire, so as to eliminate some particular vibration which might be otherwise transmitted. The galvanometer rested on platform *C*. It is a high sensitivity Leeds and Northrup moving coil galvanometer of the ballistic type and is extremely sensitive to small mechanical vibrations. The device has proved to be effective in eliminating our vibration difficulties and it is reported here, with the thought that it may aid others who have

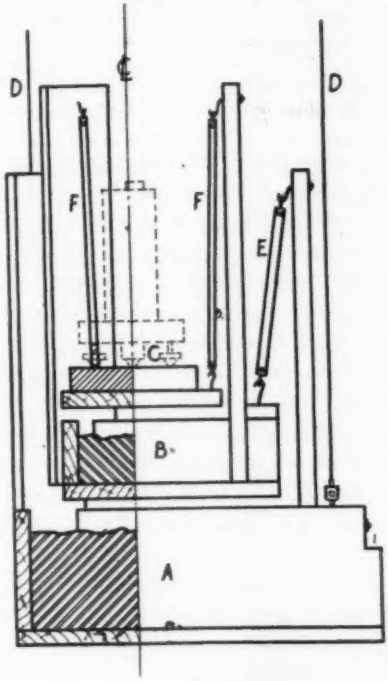


FIG. 1

similar disturbances. The device has the merit of being quickly and easily made, and of requiring no long tedious adjustment such as is demanded in setting up the usual Julius suspension. By changing lengths and sizes of suspension tubing and weights of platforms, and by adding one or more platforms, it ought to be possible to eliminate small vibrations in any case.

LABORATORY OF PHYSICS,
UNIVERSITY OF ILLINOIS,
MAY, 1922.

A FORM OF IRON CLAD THOMSON ASTATIC GALVANOMETER

By B. J. Spence

ABSTRACT

A form of iron clad Thomson astatic galvanometer of high sensibility is described. It differs from the types described in the literature in that it is semi-portable, has a removable core containing coils and suspended magnetic system, has comparatively small weight and is easily adjusted to a high sensibility.

The early forms of the iron clad Thomson astatic galvanometer of high sensibility as used for radiometric study in connection with the bolometer or thermopile were bulky, heavy, and difficult to adjust for a maximum sensibility. The galvanometer has under gone a number of modifications diminishing somewhat the weight and bulk. More recently Coblentz[1] has designed a galvanometer of this type in which he has embedded the coils in soft iron. This galvanometer appears less bulky and is perhaps easier of adjustment than the earlier forms. In connection with the development of this galvanometer he has investigated the effect of coil construction, magnetic shielding, of different types of magnetic systems and of evacuating the region in which the system is suspended. For further details the reader is referred to the Coblentz article.

The writer has attempted the development of an iron clad galvanometer in which the coils and rotating magnetic system may be removed as a unit from the shielding and which may be adjusted to a high sensitivity with more facility than the earlier forms. The attempt has been also to embody in the design the results of the Coblentz investigation.

The four coils each 13 mm in diameter and 4 mm thick were wound on a mandrel whose surface was shaped approximately according to the expression of Maxwell.[2] Instead of winding the

[1] Bureau of Standards Scientific Papers, No. 282.

[2] Maxwell, Electricity and Magnetism, vol. 2, p. 360.

coils in sections of double silk covered wire, they were wound with 12 ohms of No. 36 B. S. gauge enameled wire, boiled in half and half (50% resin and 50% bees wax) removed from the mandrel and the faces covered with gold leaf. The four coils were mounted in the two sections of a split hollow brass cylinder 15 cm long, 16 mm outer diameter and 10 mm bore (see Fig. 1). At 45 mm and 60 mm respectively from the bottom of each section were cut two circular holes 14 mm in diameter into which were cemented the four coils. When the sections of the cylinders were placed together the centres of the faces of the coils were opposite each other and 1.5 mm apart. The leads from each coil were carried to the top of each section along the flattened surface of each cylinder. At the top of one of the sections of the hollow cylinder was a removable head containing a screw which carried the suspended magnetic system. The screw could be raised or lowered and rotated for adjustment of the position of small magnets relative to the centres of the coils. When the magnetic system had been suspended by means of a fine quartz fibre the second section of the cylinder could be set in place without danger of breaking the fiber.

The magnetic system consisted of two groups of six each of tungsten steel magnets 1.2 mm long and fastened to a fine glass staff with a trace of shellac. At 30 mm from the lower group of magnets was fastened a mirror 1 mm $\times$ 1.5 mm. The system was magnetized and astaticized in the usual manner.

The shielding consisted of a cylinder of Swedish iron 18 cm long and 7.5 cm in diameter. Along the axis of the cylinder was bored a hole a trifle over 16 mm in diameter to a distance 4 cm from the bottom. A conical hole of small dimensions, 13 cm from the bottom was bored through the cylinder wall to the interior to observe the rotation of the mirror attached to the magnetic system. Over this hole was cemented a glass plate. After all machine work had been completed the cylinder was carefully annealed in an electric furnace and then keep away from contact with magnets. It was then mounted carefully on a suitable base with leveling screws. The coils and magnetic system were slipped into the shield and the whole properly adjusted until the magnetic

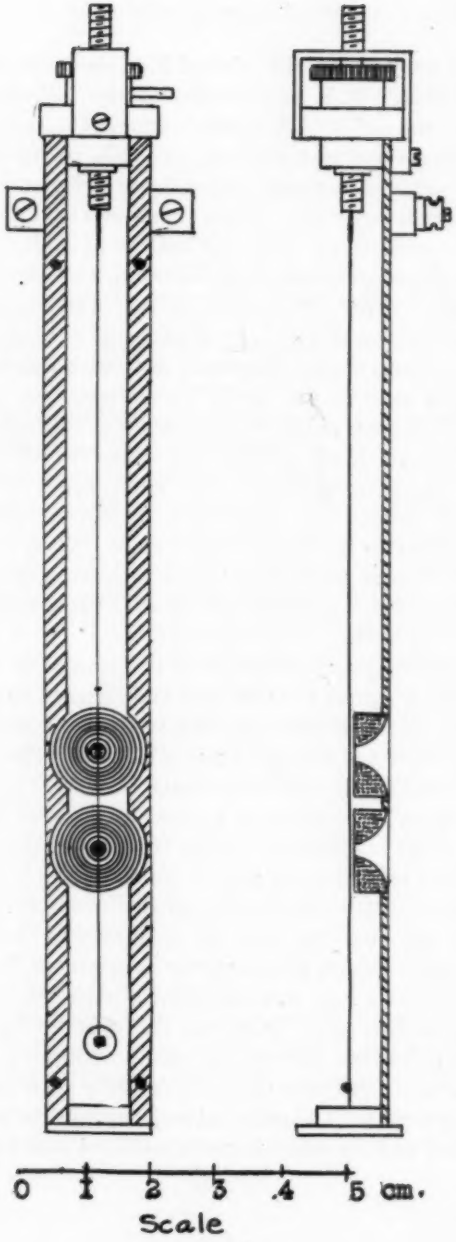


FIG. 1

system swung freely. The ease of this adjustment to a large extent depends upon the care with which the machine work has been done. If the axis of the core contained in the cylinder is perpendicular to the plane of the base the adjustment can be carried out by placing a good level on the base.

In order to control the zero and adjust the instrument for high sensitivity a weak magnet of watch or clock spring was covered with paper and shellaced and slipped about over the cylinder.

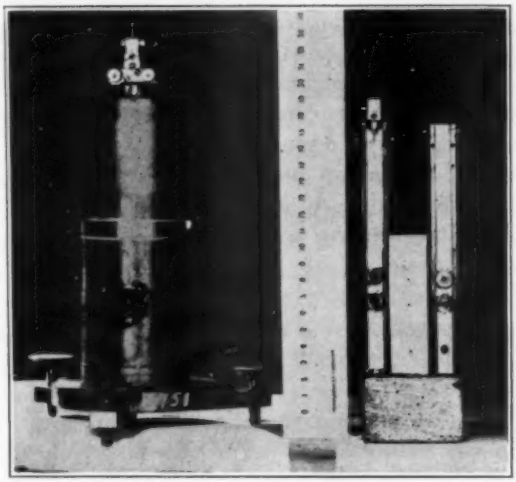


Fig. 2

By carefully manipulating this control magnet a high degree of sensitivity was attained in a comparatively short time. With this instrument of 3 ohms (coils in parallel) a sensitivity of 5×10^{-10} amperes with a scale at a meter distance could be attained readily. The period was about 1.5 seconds. The shielding appeared to be ample for this sensitivity. No zero drift manifested itself due to external magnetic disturbances. There was, however, considerable rapid zero fluctuation of about 2 mm due to building vibrations. These disturbances were amplified by the rotating system owing to the fact that the control magnet intro-

duced a non-uniform field in the core. A slight displacement due to building vibrations shifted the system slightly into a field of different strength and produced and amplified vibration of the system. The sensitivity was increased to 8×10^{-12} amperes with a period of 3 seconds by increasing the shielding and operating the system in vacuo. The additional shielding was made of a roll of stove pipe iron 20 cm wide with the turns separated by paper and then placed on the base concentric with the Swedish iron. A cap was cemented on top of the Swedish iron shield and the pressure in the core lowered to 1 mm.

In conclusion it may be stated that a semi portable form of iron clad Thomson astatic galvanometer of high sensibility has been developed which is comparatively simple of construction, has small bulk and is comparatively easy to adjust. It had embodied in it the feature of removable core containing system and coils. I am indebted to Mr. F. Kung, our mechanician, who patiently worked out many details of the instrument.

NORTHWESTERN UNIVERSITY,
JUNE 7, 1922.

A LOW VOLTAGE CATHODE RAY OSCILLOGRAPH

By J. B. Johnson

ABSTRACT

A sensitive cathode ray oscillograph tube is described which operates at a low voltage. The electron stream comes from a thermionic cathode, and is focused by the action of the ionized gas in the tube. Illustrations show examples of the use of the tube.

A cathode ray oscillograph tube operating at a comparatively low voltage was described by the writer some time ago before the American Physical Society.[1] Since then, the tube has been further improved and its operation studied so that now both the structure of the tube and the principles which have made the construction possible can be described in greater detail.

In the older types of Braun tubes the electron stream is produced by a high voltage discharge through the residual gas in the tube. This requires a source of steady potential of from 10 000 to 50 000 volts, an installation which is expensive, non-portable, and dangerous. In the new type of tube the low voltage operation has been obtained by the use of a Wehnelt cathode as the source of electrons, so that the lower limit of voltage is set by the effect of the electrons on the fluorescent screen and not by the voltage needed to obtain the electrons. At 300 volts the electrons produce quite bright fluorescence on the screen and the tubes are therefore designed to operate at 300 to 400 volts.

The external appearance of the tube is shown in Fig. 1. The electrodes are located at one end of the pear-shaped bulb, and the fluorescent material is deposited on the inside of the larger, flattened end. The tube is provided with a base which fits into a bayonet socket such as is used for vacuum tubes, and all the connections are made through the base. There are two orthogonal pairs of deflector plates inside the tube for electrostatic deflection, while magnetic deflection is produced by applying a field from the outside.

[1] Phys. Rev. (2), *17*, p. 420; 1920.

The internal structure differs considerably from that of previous forms of Braun tube and it will therefore be described somewhat fully.

THE FOCUSING

In some forms of Braun tube a sharp spot has been secured by using a very high voltage, and therefore high electron velocity,

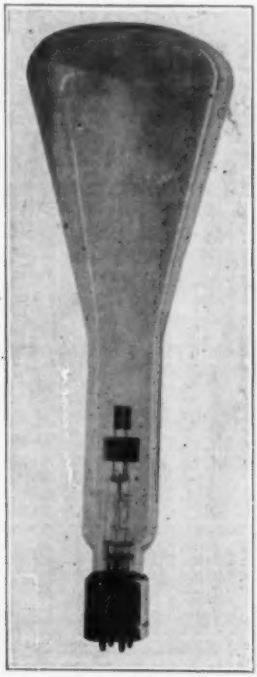


FIG. 1. The Cathode Ray Oscillograph Tube

so that after the electrons have passed through one or two fine apertures to make the beam parallel there is not time enough for the mutual repulsion to spread the beam again appreciably before the electrons strike the screen. With other tubes an external

"striction" coil has been used which maintains a strong longitudinal magnetic field in the region between the anode and the cathode and which brings the electrons to a focus on the screen. In the low voltage tube the spreading of the electron stream is greater than in high voltage tubes because of the greater time during which the mutual repulsion of the electrons acts, so that some means of focusing must be used. The electrons can be brought to a focus by a longitudinal magnetic field so adjusted that each divergent electron makes very nearly one complete turn of a spiral and in travelling the length of the tube returns to the axis at the screen. In this way a very sharp spot can be produced, but the sensitivity of the beam to deflection is reduced very much by the directing magnetic field.

The method of focusing that is used in the present tubes grew out of the suggestion by Dr. H. J. van der Bijl, that a small amount of gas be introduced into the tube. This gas, at a pressure of a few thousandths of a millimeter of mercury, serves to reduce to 1 mm diameter a spot which would be 1 cm across in a high vacuum tube. The sharpness of the spot depends also upon the current in the electron stream so that the focus may be controlled by the cathode temperature. The mechanism of this focusing action will be explained later.

The presence of this slightly ionized gas also serves the purpose of preventing the accumulation of charges on the glass, and it provides for the discharging of the fluorescent screen so that the electrons can drift back to the metallic circuit.

THE ELECTRODE UNIT

With gas present in the tube, steps have to be taken to guard against arcing and the injurious effects of positive ion bombardment on the cathode. This is done by making the volume of gas surrounding the electrodes very small. For this purpose the cathode and anode, themselves small, are sealed into a short and narrow glass tube so that the volume exposed to both electrodes in common is less than 1 cm^3. All paths between the electrodes are then so short that at this low pressure there is not sufficient ionization to build up an arc.

The structure of this unit, or "electron gun" is shown in Fig. 2. The cathode, *f*, is an oxide coated platinum ribbon of the same kind as the filament in our audion tubes. The anode, *a*, is a thin platinum tube 1 cm long and 1 mm in diameter, one end of which is about 1 mm from the top of the filament loop, the other end opening into the main tube towards the fluorescent screen.

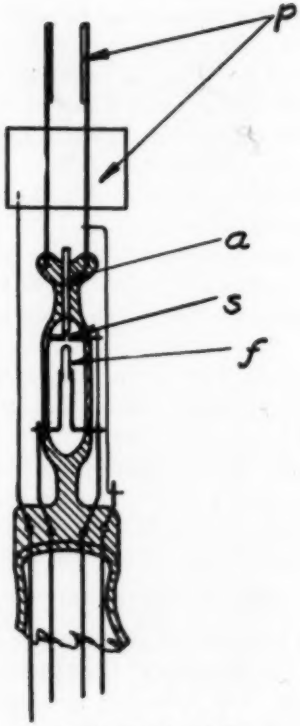


FIG. 2. The Electrode Unit

Between the cathode and the anode and connected to the cathode is a metal shield, *s*, with a small aperture through which the electrons must pass in going to the anode. Nearly all of the electrons must then go to the inside of the tubular anode, and a

small fraction of them passes through the whole length of the anode and form the beam in the main part of the tube.

The deflector plates, p, are also mounted rigidly on this unit. In order to avoid large differences of potential in the tube, one plate from each pair is permanently connected to the anode, the variable potentials being applied to the other plates. The complete unit is mounted at the small end of the tube with the anode and deflector plates toward the fluorescent screen.

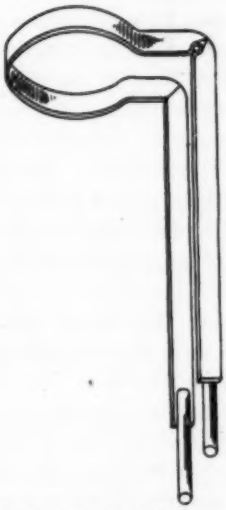


FIG. 3. The Thermionic Filament

THE FILAMENT

In some early forms the filament was bent into a simple hair pin loop which was placed close to the aperture in the shield. It was then found that the positive ions striking the filament from the direction of the anode soon destroyed the oxide coating and left the filament inactive. This trouble was largely overcome by placing the filament out of the direct path of the positive ions. The flat filament is now shaped into a ring as shown in Fig. 3, slightly larger in diameter than the aperture in the shield and is

placed coaxial with the anode. The momentum of the positive ions then carries them past the active part of the filament and they strike where little damage can be done. The length of service of the tube is still limited by the filament life, but this has been increased by the above artifice so that the tube now gives around 200 hours of actual operation.

THE DEFLECTOR ELEMENTS

The deflector plates are made of German silver, which is non-magnetic and which has a high specific resistance that diminishes the effect of eddy currents when magnetic deflection is used. The plates are 13.7 mm long in the direction of the tube axis and the separation between them is 4.7 mm.

The sensitivity of the tube is such that the deflection of the spot is about one mm per volt applied between the deflector plates. When using magnetic deflection, a pair of coils 4 cm in diameter placed on the sides of the tube at the level of the deflector plates produce a deflection of approximately 1 mm per ampere-turn flowing in the coils.

The electrons striking the screen drift back to the anode structure, and most of them are collected by the deflector plates. There is also a small ionization current flowing to the plates. The tube is therefore not strictly an electrostatic device, and this must be kept in mind when using it. Fig. 4 shows the current flowing to the two free plates at various voltages with respect to the anode. With the large positive values of plate voltage the current to the plates is practically equal to the current in the electron stream and consists largely of the returning electrons. The small current in the other direction when the plate voltage is negative is a measure of the ionization in the tube.

THE FLUORESCENT SCREEN

The screen is spread on the inner surface of the large end of the tube, using pure water glass for binder. The active material consists of equal parts of calcium tungstate and zinc silicate, both specially prepared for fluorescence. This mixture produces a generally more useful screen than either constituent alone. The

pure tungstate gives a deep blue light which is about 30 times as active on the photographic plate as the yellow-green light of the silicate, while the silicate gives a light which is many times brighter visually than that from the tungstate. By mixing the two materials in equal parts a screen is produced which is more than half as bright visually as pure zinc silicate and more than half as active photographically as pure calcium tungstate.

For mechanical strength the end of the bulb which carries the screen is rounded outwards so that the screen is not a plane sur-

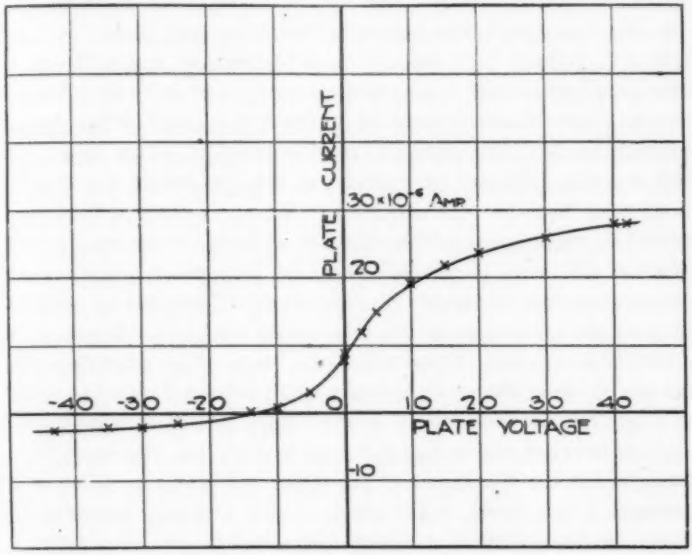


FIG. 4. Current to Deflector Plates

face. This introduces a distortion of the fluorescent pattern which in most instances is negligible. If the pattern is recorded by a camera whose lens is D cm. from the end of the tube, then the apparent reduction of the deflection produced by the curvature of the bulb is given in terms of the deflection y approximately by

$$\Delta y = \frac{20+D}{400D}\, y^3 \text{ cm.}$$

THE FUNCTION OF THE GAS

The part which the gas plays in focusing the beam of electrons is an interesting phenomenon which depends upon the difference in the mobilities of electrons and positive ions. The electrons of the beam are pulled toward the common axis by a radial electric field produced by an excess of positive electricity in the electron stream and an excess of negative electricity in the space outside the beam. This distribution is produced as follows. Some of the electrons of the stream, in passing through the gas, collide with gas molecules and ionize them. Both the colliding electrons and the secondary electrons leave the beam but the heavy positive ions receive very little velocity from the impact and drift out of the beam with only their comparatively low thermal velocity. Positive ions therefore accumulate down the length of the stream and may exceed in number the negative charges passing along. At the same time, electrons are moving at random outside the stream, producing negative electrification. There is then a field surrounding the stream which tends to pull the electrons inward. If there were only the mutual repulsion between the electrons to compensate for, this would be done when the number of positive ions in the beam equals the number of electrons. There is in addition an original divergence of the beam which must be overcome. If this divergence is assumed to be one degree from the axis and the electron current 2×10^{-5} amp, then a simple calculation shows that the radial field required to pull the beam to a focus at the usual distance is about one volt per cm. This field strength is produced, with beams of the ordinary intensity, if there are four positive ions for each electron in the stream, a condition which seems not unreasonable.

The number of ions per electron in the stream is probably constant as the current in the stream is varied, since the conditions of collision and recombination are not altered. When the current is increased, therefore, the total positive ionization of the beam increases, the field around the beam becomes stronger, and the electrons are brought to a focus in a shorter distance.

These deductions have been confirmed experimentally. That the focusing of the stream depends upon the current flowing

was one of the earliest observations made in developing the tube and this method had been used ever since to obtain a sharp spot. The point of convergence can be seen moving in the manner expected when the current is changed, and the effect has been further verified by using a tube with a movable fluorescent screen so that the length of the electron beam could be varied. The presence of the electric field around the beam was shown by the effect of two beams on each other, in a tube in which there were two electron streams crossing each other at right angles at their mid-points, each falling on a fluorescent screen. When one beam was moved away from the other by a field between the deflector plates, the second beam moved as if attracted by the first. The directed electrons in each beam were attracted toward the positive ionization in the other, and for one particular adjustment of the tube the displacement was such as would have been caused by a field of about 3 volts per cm, a result not far different from that previously calculated.

Since the beam must produce its own positive ionization some time must elapse before it can produce by collisions the required number of positive ions. Calculation shows this time to be of the order of 10^{-6} second. When the beam moves it has to build up the ionization as it goes along, and we should expect that when deflected very rapidly it might no longer be focused, due to lack of positive ions in its path. A test was made of this by applying a high frequency potential on the deflector plates so that the spot described an elliptic pattern. At a frequency of 10^5 cycles per second the line was still sharp, but at 10^6 cycles there was a noticeable widening of the line which is probably to be ascribed to imperfect focusing at this high speed.

In these experiments the evidence all points to the view that the focusing of the electrons is caused by an excess of positive charge in the beam itself, produced by the ionizing collisions of the electrons with the gas molecules. Further confirmation is found in the fact that a focus is much more readily obtained in the heavier gases having slow molecules, such as nitrogen, argon or mercury vapor, than in hydrogen and helium where the mean velocity of the molecules is greater. The tubes are therefore

filled with argon, the heaviest available permanent gas which does not attack the electrodes. The best pressure for the length of tube adopted and for the current which can be obtained in the beam is 5 to 10 microns, and this leaves considerable latitude for the adjustment of the electron current to get a sharp focus.

EXAMPLES OF THE USE OF THE TUBE

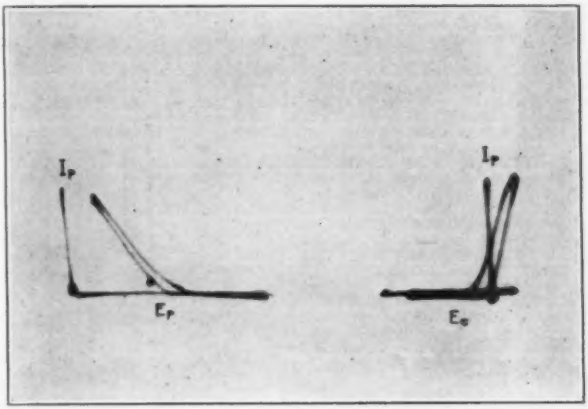
Because of the small amount of auxiliary apparatus required with this form of Braun tube it has proved to be a very convenient

FIG. 5. Iron Hysteresis Curve

laboratory instrument. It has found application in studying the behavior of vacuum tubes and amplifier and oscillator circuits, of gas discharge tubes, of relays, and of numerous other kinds of apparatus, both at low and at high frequencies. Some reproductions of photographs of various types of curves are given below to illustrate the kind of results which are possible with this oscillograph.

Fig. 5 shows the hysteresis curve of a sample of iron wire. The wire was placed in a small solenoid with one end toward the side of the tube. The magnetizing current passed through a resistance,

the voltage drop of which was applied to one pair of deflector plates so as to give a deflection proportional to the magnetizing field. The stray magnetic field from the iron itself produced the deflection proportional to the induction. Alternating current was used, and the exposure was 20 seconds with lens opening *f* 6.3 and speed roll film.



a *b*

FIG. 6. Characteristics of Oscillating Vacuum Tube

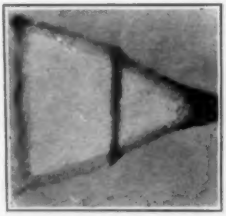


FIG. 7. Modulation of High Frequency Current

In Figs. 6a and 6b are shown the current-voltage relations of an oscillating vacuum tube. The axes were obtained by grounding one or the other deflector element.

The measurement of modulation in a radio transmitting set has been reduced to a fairly simple process by means of the cathode ray tube. The low frequency modulating voltage, controlled by the voice, is applied to one pair of deflector plates, while the radio frequency output, with amplitude varying according to the low frequency voltage, is applied to the other pair of deflector plates. The resulting pattern on the screen is a quadrilateral of solid fluorescence, since the two frequencies are not commensurate. The two vertical sides indicate the greatest and the least amplitude of the high frequency, while the other two sides show the current-voltage characteristic of the transmitter. Fig. 7 shows such a pattern (retouched), the edges being much brighter than the center. The exposure was two minutes using a Seed 23 plate and f 6.8 lens opening.

RESEARCH LABORATORIES OF THE
WESTERN ELECTRIC CO., INC. AND THE
AMERICAN TELEPHONE AND
TELEGRAPH COMPANY
NEW YORK CITY

SPECIFICATIONS FOR RECORDING VAPOR-PRESSURE THERMOMETERS AND FOR PRESSURE GAGES

By Frederick J. Schlink

The specifications for recording thermometers and for reference standard pressure gages, the first of which are presented below, are believed to be the first specifications applying to these instruments ever published, although with respect to pressure gages of the more usual or service types, some codes of specifications more limited to constructional arrangements and details have been available heretofore. The present specifications for service pressure gages will be found to differ from existing codes in many important essentials, and to extend the scope and precision of specified requirements to a significant degree. Points of marked difference from common practice will be noted in the following: the zero stop pin eliminated, permitting secular changes of the Bourdon tube to be noted on the dial, as they occur; graduation circles required to fill substantially the whole dial diameter; the rated maximum pressure capacity established as the actual upper operating limit of the gage, rather than 100% higher, as is now a common practice with some makers; anomalous graduations in the zero region of the dial eliminated (for instance, four graduations in the first five pound interval have been almost the regular practice in American made gages, following some traditional error of an early gage maker; the present specifications prefer to permit omission of these first few graduations, in the region where the scale factor is not constant, and backlash is a special source of difficulty). Other points are the restriction of the radial length and thickness of graduation lines so as to increase the accuracy of readings; and the basing of the tolerances of error on the value of the minimum graduation. This latter, in a very real sense, the maker holds out as a measure of the precision of his instrument and to this therefore the tolerances should be clearly related

when once the user has decided how small the minimum graduation need be to meet the requirements of his service. It may be said in passing that the tolerances herein set down are perfectly practical and attainable ones in respect to new gages of good manufacture with the types of graduation customary in the United States (40 to 80 graduations in 270° of arc). Considerable purchases have been made under the requirements of these specifications at little or no increase in price, but with a very significant increase in quality over the ordinary product, which experience and extensive investigation have shown to be surprisingly variable as between different makers and even between different samples of a given maker's product.

These specifications were used to control purchases of all instruments of the types named, employed in production departments of the Firestone Tire and Rubber Company at Akron, Ohio; and the marked success met with in their application in spite of the radical changes in construction and details which in some respects they require, has led to their publication in the hope that they may be of general interest and utility.

The degree of precision attainable with properly selected instruments of these two types under proper conditions of use, is quite surprising, and such as to make them adaptable to many of the uses of the physicist. For instance pressure gages, when used under proper cyclicization before reading, or when jarred energetically by a securely mounted buzzer, can give results accurate to $\pm 0.1\%$ under laboratory conditions when a calibration curve is used; while a recording thermometer of the vapor-pressure type, meeting these specifications in all essentials, will record temperatures over a limited range, say 25°, within ± 0.1° C, when a calibration curve is used, and the instrument is occasionally checked at some convenient reference temperature. In fact there are applications wherein the vapor-pressure recording thermometer, in view of its freedom from variable stem immersion errors, may afford a net accuracy definitely superior to that of a good mercurial thermometer.

JUNE 25, 1922.

SPECIFICATIONS FOR VAPOR-PRESSURE TYPE RECORDING THERMOMETERS AND CHARTS

June 11, 1920.

1. GENERAL REQUIREMENTS

a. *Type.* These recording thermometers shall be of the vapor pressure type, so as to be substantially unaffected in their readings by the temperature of the tube connecting the bulb and the registering element.

b. *Use.* These recording thermometers are to be used to determine the temperature of (here define conditions of use fully and specifically to permit of proper design and choice of material of bulb, etc.)

2. IDENTIFICATION OF INSTRUMENTS

a. Each recording thermometer shall be equipped with an identification plate plainly visible without requiring the removal of any part of the mechanism, on which shall be clearly and permanently inscribed: the type and maker of the instrument; the month and year of manufacture; the range of registration; identification number of the chart used; and the intended relationship between the elevation of the bulb and that of the recording element. The information furnished shall be at least as complete as in the following specimen:

Recording thermometer, vapor-pressure type.
Maker: The Jones Company—Mar. 1919, (or 3-'19.)
200–300°F. Chart 721.
Bulb 10 ft. below Bourdon Tube.

3. CASE CONSTRUCTION

a. *General.* The construction of the case, in respect to strength, rigidity and dust tightness, shall be the equal of that used on ———— recording thermometers, as described and illustrated (name catalog and page or other defining reference).

b. *Door and Hinge.* The door hinge shall be of strong and durable construction with an adequate amount of metal to withstand such bending and twisting strains as the door may commonly be subjected to in plant service. The door shall be equipped with plate glass of good quality so set into the door frame as to comply substantially with the requirements as to dust tightness provided for above. The hasp and staple of these recording thermometers shall be adapted to take, easily, a lock having a staple diameter of 7/32", the radius of the center line of this lock staple being approximately 5/16".

c. *Finish.* The surface finish of these instruments shall be neat and shall afford a protective coating of such thickness and durability as to protect the material of the case from the effects of moisture and abrasion in reasonable plant service.

d. *Holes for Mounting.* These recording thermometers shall be provided with at least three screw holes approximately 0.25 inch in diameter, by which the instrument may be secured to a supporting surface. If the case is of circular outline, the screw holes shall be spaced at equal angles, one of these holes to be located exactly at the top or bottom position.

4. RESPONSIVENESS

a. Time response.

The time-quickness of response of these recording thermometers to changes of temperature shall be the maximum possible without requiring too great reduction of

the bursting strength of the bulb. The minimum wall thickness and maximum heat conductivity of the bulb shall be employed consistent with the requirements of strength, corrosion resistance, and other essentials.

b. Temperature response.

These recording thermometers shall respond to a change of temperature of 0.3°F. or less; that is, the passiveness, as defined on page 745 of Bureau of Standards Scientific Paper 328[1] shall not exceed 0.3° F. over the temperature region between ——— and ———° F. The present specification refers to the minimum change of temperature as the result of which the instrument will show a discernible change of indication, regardless of the direction or amount of the antecedent movement of the recording pen. This factor is to be clearly discriminated from that covered by the preceding specification, which refers to the promptness of response.

5. Arrangement of Bulb

a. The sensitive and active portion of the bulbs of these recording thermometers shall be so constructed and so isolated by the distance of their projection beyond the union or by necking down of the bulb wall back of the bulb or by these and other suitable means,—from the remainder of the instrument tubing and connections, that when the bulb connection is screwed within a standard pipe fitting or the walls of a vessel containing saturated steam in movement past said bulb, the temperature readings will be substantially unaffected by the temperature of the walls of the vessel at and adjacent to the point where the bulb fitting is applied. The maker shall specify the minimum radial distance to be provided around the bulb when the stem is screwed longitudinally into a standard pipe fitting in order that the temperature readings will not be affected to the extent provided for in the tolerance hereinafter to be specified. No separable sockets are to be furnished or used in calibration. A union, to avoid the necessity of twisting the capillary tubing in applying the instrument, shall be provided, of standard pipe thread size not in excess of ¾″.

6. Armoring of Capillary

a. The protecting armor, if any is employed, around the capillary tube, shall be similar and equal to that used in the ———— Company's flexible, bronze-armored capillary tubing. Protecting armor will not be essential provided that a sufficiently rugged solid wall copper or bronze tube of reasonable flexibility is furnished, subject to prior approval of sample by the purchaser. The capillary tube and its armor, at the point where these enter the case of the instrument shall be reinforced and rigidly and permanently secured to the case in such a manner as to protect the capillary tube from strains of a character likely to deteriorate or otherwise damage it.

7. Clocks

a. The clocks to be furnished in these recording thermometers shall be of such construction that they will run at least 50 hours on one winding and during the first 24 hours of running their deviation from correct time shall not exceed 5 minutes at a temperature of 80° F., while during the second 24 hours the deviation shall not exceed 10 minutes. The clock movements shall be enclosed in dust-tight metallic boxes within the case of the recording thermometer.

[1] Variance of Measuring Instruments and its Relation to Accuracy and Sensitivity, by the present author.

8. RECORDING PENS

a. The pens of these recording thermometers shall be of the V-type and shall be made of material that will not corrode under the action of an ink composed of an aqueous and glyceric solution of dye. These pens shall be accurately and carefully finished and rigidly and neatly secured to the pen arm. The means of attachment of the pen to the pen arm is preferably to be one that will permit of removal without the necessity of unsoldering a joint.

9. QUALITY OF RECORD

a. The pen line drawn by these recording thermometers shall be of uniform width not exceeding .005 inch and the pen shall draw a full, solid line at any speed of travel relative to the chart not exceeding 2 inches per minute.

10. PEN ARM LIFTER

a. These recording thermometers shall be equipped with a pen lifting device so constructed and positioned that the chart may be readily removed without danger of straining the pen movement or pen arm, and operating so as to return the pen to the recording position automatically on closing the door of the case.

11. PEN ARM ADJUSTMENT

a. The pen arm adjusting device used on these recording thermometers shall be of such construction that it will require no lock nut or equivalent device. Its movement shall be sufficiently stiff, or so restrained by the action of a split nut or screw or other permanently effective means, that it can be accurately controlled in its movement, and will maintain its setting permanently.

12. ATTACHMENT OF CHART CLAMPING SCREW

a. The chart clamping screw or other device used to secure the chart to its driving arbor, shall be loosely connected to a fixed part of the case of the recording thermometer, by a convenient length of chain, so as to prevent inadvertent loss of this screw during the chart-changing operation. This chain must be so arranged as not to interfere in any way with the movement of the recording pen, or the clock arbor, or with the closing of the case door.

13. ACCESSORIES

a. Each recording thermometer shall be accompanied by 100 charts of the proper type, one bottle of non-corrosive, slow-drying ink, and a clock winding key. No padlocks or other locks for the cases are to be supplied unless specifically stated in the order.

14. CHARTS

a. *Paper and Printing.* The charts shall be made of a quality of paper such that excessive alteration of dimensions with changes in atmospheric humidity, and lateral spreading of the record line, will not occur. The arrangement and numbering of lines and graduations shall be such as to afford a maximum of ease and accuracy in reading. Preference will be given to charts printed in olive green or gray or other neutral tint.

b. *Centering.* There shall be no measurable difference between the diameter of the centering hole of the chart and that of the arbor or spindle upon which it is mounted when in use on the instrument. The burring of centering holes or of peripheries in any charts or eccentricity of punching in excess of .003 inch, will constitute cause for rejection of the whole lot of which they form a part.

15. TOLERANCE

a. These recording thermometers shall exhibit no error at any point of their graduated scale, due to any cause, greater than ±1°F.; nor greater than ±0.5°F.[2] at any single point of their range of graduation specified in the order; provided that in respect to the former value no tolerance smaller than that equivalent to .03 inch of pen movement and in respect to the second value no tolerance smaller than that equivalent to .015 inch of pen movement, shall be applied.

16. PERMANENCE OF ADJUSTMENT

a. The quality and aging of the Bourdon tubes shall be such that no secular change of reading at a given temperature subsequently applied, greater than that equivalent to .015 inch of pen movement, will occur during an interval of one month, during which the instrument is out of use or in stock. Moreover when subjected to an oscillatory temperature test having an amplitude between the innermost graduation of the chart and an upper limit lying 10° F. or more below the outermost graduation circle carried out at a rate not to exceed one cycle every five minutes, over a period of twenty-four hours, these instruments shall develop no errors in excess of the tolerances provided in the foregoing specification.

AMERICAN ENGINEERING STANDARDS COMMITTEE,
29 W. 39TH ST., NEW YORK CITY.

[2] These limits applicable, like that in Specification 4-b, to instruments operated through a temperature interval not exceeding 250° F. For larger intervals of indication, the tolerance will need be proportionately increased.

SIEVE TESTING APPARATUS

By L. V. Judson and R. E. Gould

There has recently been developed at the Bureau of Standards a new projection apparatus intended primarily for the testing of sieves, but readily adaptable to various other purposes.[1]

The Bureau has found by experience that in testing sieves for conformity to the "Standard Specifications for Sieves," the most reliable results are obtained by measuring the wire diameters and determining the number of wires per centimeter, and then computing the opening by the formula

$$O = \frac{10}{N} - W$$

where O = average opening in millimeters

N = number of wires per centimeter

W = average diameter of the wires in millimeters.

Until recently the wires have been measured directly by means of a micrometer microscope. As this process is both tedious and fatiguing to the eyes, a better method was sought. The projection method developed is much quicker and much less wearing on the observer than was the method formerly used. Measurements can be taken on any number of the warp and of the shoot wires of the cloth, and the cloth also examined for maximum openings in a small fraction of the time formerly required.

The final development of this apparatus consisted of several steps: The construction of a suitable light-tight box of proper dimensions; the selection of a microscope combination to give the best general results, of the light source and its location, and of the screen on which the image is cast; the development of a method of measuring this image so as to avoid parallax, of a means of reducing to a minimum the color bands on the edge of the image, and of

[1] The final form of this apparatus was developed after seeing photographs of a projection apparatus developed by Mr. Schoof of the Greenfield Tap & Die Corporation.

a device for focusing and for moving the sieve at right angles to the beam of light. The apparatus at present consists of a light-tight box about 40 cm square and a meter long with a microscope mounted on one end and a ground glass plate 2 mm thick in the other end. The source of illumination is a microscope illuminator containing a concentrated filament lamp, 6 volts, 108 Watts, connected through a transformer to a 110-volt alternating current supply circuit. The light passes through a lens in the end of the illuminator and is focused on the objective of the microscope.

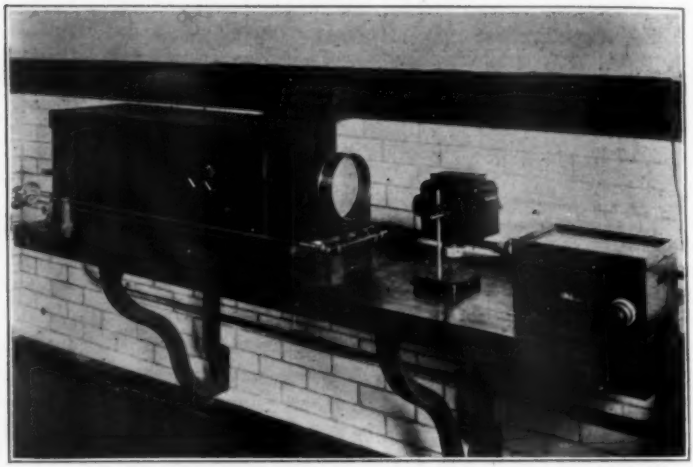


FIG. 1. Sieve Testing Apparatus

After passing through the microscope it diverges to the ground glass plate which is mounted with the ground side in. A 50-cm steel scale is mounted against the inner face of the ground glass screen in such a way that the graduations of the scale may be seen through the glass. The position of the scale allows a direct reading on the edges of the image cast by the wire of the sieve and avoids parallax due to the thickness of the glass. It was found that by oiling the ground surface slightly, the visibility was greatly increased without diminishing the distinctness of the image.

A frame for holding the sieve is placed on a platform so ar-

ranged as to permit a lateral motion of about 8 inches, and also motion at right angles for focusing. Long rods, extending to the end of the apparatus at which the observer is seated, enable the observer to move the sieve without leaving his place, the lateral motion being accomplished by means of a rack and pinion and the focusing by the use of beveled gears. A green filter is held before the objective by means of a clamp fastened to the tube of the microscope. The filter relieves eye strain very considerably and practically eliminates the color bands otherwise appearing on the edges of the image.

In use, the sieve is mounted in its holder on the focusing platform, between the illuminator and the objective of the microscope, and is focused by the observer until a sharp image is seen on the ground glass. Measurements are then taken in millimeters by reading the positions on the steel scale where the two edges of the image of the wire cross it, a reading glass being sometimes used. The sieve is then moved across the field, readings being taken at several places on the cloth, until the whole diameter of the sieve has been covered, care being taken at the same time to watch for the uniformity of spacing and to measure any excessively large openings. The sieve is then rotated through 90° and the process repeated.

The magnification of the apparatus may be determined by placing a standard wire of known diameter in place of the sieve and making several readings on its image. This should be done at least twice a day to guard against any possible change in magnification while the apparatus is being used.

By using a microscope having a tube about 15 cm long and an eyepiece with a magnifying power of approximately three diameters, together with a 16 mm objective, a magnification of about 260 diameters is obtained. This is found to be very satisfactory for the fine-mesh sieves. Measurements good to 0.2 mm can be made of the image as seen on the ground glass plate, individual readings repeating to 0.5 mm or better. This gives an accuracy of better than 0.001 mm for the average wire diameters and width of opening.

BUREAU OF STANDARDS,
WASHINGTON, D. C.,
JULY 24, 1922.

THE FILM METHOD OF MEASURING SURFACE AND INTERFACIAL TENSION

By A. W. Fahrenwald

Many methods of measuring surface tension are available. The most important among them are (1) the drop-weight method (2) the capillary rise method (3) the Jaeger or capillary bubble method (4) vibrating jet methods (5) methods measuring the tension required to detach a ring, sphere or disc from the surface of the liquid, and (6) the film method.

More attention has been given to the drop-weight method than to any one of the other methods mentioned. The work of Morgan, Richards, Ferguson and of Harkins and his students has resulted in a high refinement and reliability of this method. However, it should be pointed out that there are factors that enter into its accuracy that cannot be overlooked if trustworthy results are to be obtained. They are (1) the rate of dropping (2) the diameter, shape, and material of dropping tip, and lastly the proper corrective factors must be applied if absolute figures are desired. Further the drop-weight method measures the tension in relatively fresh surfaces, and it is, therefore, not satisfactory when the tension of relatively older surfaces is desired. A method that measures the tension of fresh surfaces is not nearly as sensitive to slight changes in interior concentration of a liquid as one that measures the tension in older ones. Another serious objection to the drop-weight method when working with many liquids, each having different rates of adsorption of certain surface tension lowering constituents in its surface, is the strict requirement of rate of dropping. Even though the rate of dropping be absolutely constant for all measurements there is still the uncertainty of reliability of the relative value of the results due to the different rates at which the different substances go into the water surface. For the above reasons it proved to be unsatisfactory in working with oil and water emulsions and solutions in the determination of oil adsorption by minerals.

The second method is accurate but considerable skill and care are required in making measurements by its use. Clean and uniform capillary tubes and zero contact angles are pre-requisites. It is rather slow and is not a good method for every day laboratory work.

The Jaeger or capillary bubble method[1] depends on the measurement of the maximum pressure required to force out a bubble of gas from a capillary tube whose circular knife edge opening dips just below the surface of the liquid. As Ferguson[2] has pointed out, this method is more accurate than the capillary rise method.

Ferguson's work was on pure liquids and it is doubtful if this statement would apply in the case of liquids containing contaminants.

As with the drop-weight and vibrating jet methods, it measures the tension of fresh surfaces only. The tension in an old surface in which adsorption of the surface tension lowering constituent has been partially or entirely complete, cannot be determined by this method. It is therefore unsuitable for determining the adsorption of oils by minerals where the surface tension method is used.

To illustrate how the surface tension of an oil-water emulsion depends upon the age of the surface the following figures are given for the surface tension of an emulsion of a steam-distilled pine-oil in water (23 mg in 100 cc water) by three different methods:

Jaeger Method	65	dynes at 20° C
Drop-weight Method	63	" " " "
Film Method on circulation[3]	57.5	" " " "

[1] "Investigation on Temperature Coefficients of the Free Surface Energy of Liquids." Part I Methods and Apparatus F. M. Jaeger, Verstag Akad. Weten Schappen, *23*, 330–65; 1914.

[2] "Surface Tensions of Liquids in Contact with Different Gases." Phil. Mag., *28*, Series 6, p. 403; 1914.

[3] The surface tension of an oil-water emulsion is brought to equilibrium by circulating the emulsion with a pipette. The emulsion is drawn up a number of times, into the pipette and allowed to discharge under the surface of the emulsion. This gives efficient circulation to the body of the emulsion without disturbing the surface film. This treatment is necessary with all oil-water emulsions, in order to get readings that can be duplicated. It takes from 1 to 15 circulations to bring the surface to a point where the surface tension remains constant.

To further illustrate the advantage of the film method over the other two methods for the determination of adsorption of the oil from the above emulsion by minerals the following experiment is given:

Oil in Water mg	Surface Tension of Emulsion		Difference	Method
	Before Treatment Dynes	After Treatment Dynes		
23	65.0	65.2	.2	Jaeger
23	63.0	65.3	.3	Drop-Weight
23	57.5	60.5	2.0	Film

In many cases the Jaeger method will not show more than from .1 to .3 dynes increase in the surface tension of an emulsion before and after adsorption of some of the oil by mineral particles.

Vibrating Jet methods are entirely unsuitable for general work.

Methods under (5) give values in all cases higher than the actual surface tension. To obtain theoretical values a complicated formula has to be used. The reason is, that a column of the liquid is raised, by the ring or bar, above the surface of the liquid and in the case of a ring or bar values higher by from 1 to 10 per cent of the tension in the surface, depending upon the thickness of the edge pulled from the liquid, will be obtained.

Fig. 1 shows what happens when a straight edge is pulled from the surface of a liquid that wets it. The liquid in the portions *a a*, raised above the plane surface of the liquid is that due to capillary attraction of the liquid for the metal and is a measure of the tension in the liquid film. The liquid in the rectangular portion *b* is due to the attraction of the metal plate for the liquid molecules and the width and weight of this hydraulic column depends upon the thickness of the edge pulled from the surface, and surface tension measurements are too high by amounts which increase with the thickness of the edge used. For an edge ground to the thinness of a safety razor blade, the surface tension for water as measured by this method will be approximately one dyne too

high. The liquid in the rectangular space *b* disappears to a negligable degree when the film forms.

The film method of measuring surface tension was first used by Mickaelson and Hall.[4] Their method or device for forming the films was essentially the same as that used by the present writer; however, they did not extend it to the use of measuring interfacial tensions. Physicists have recognized the sensitiveness of the method of measuring the tension in films. Allan Ferguson[5] includes it among the most sensitive of methods but states that owing to the impossibility of forming films of sufficiently long life for an accurate measure of the tension, it has never found practical application. Hall used an analytical balance for weighing

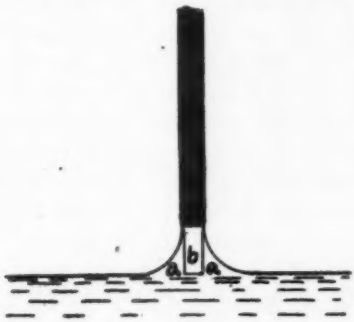


FIG. 1. Showing condition of the Liquid just before the Film is formed

the tensions in the films he worked with. This method is slow and cumbersome and the weighing process is too slow in the case of most liquids, to weigh accurately the tension in the formed film which in many cases endures for not more than a second.

This method of measuring surface tension, has, however, been taken advantage of and made practical by the use of an automatic balance, the sensitiveness of which is not quite as great as that of an analytical balance, but measurements reproducible to 1/10

[4] "New Methods of Measuring the Surface Tension of Liquids." T. Proctor Hall, Phil. Mag. Fifth Series, *36*, p. 385; 1893.

[5] "Critical Review of Some Twenty Methods of Measuring Surface Tension," Science Progress. Jan. 1915, p. 428.

dyne per cm are easily possible. This is sufficiently close for a rather wide variety of technical work.

In text books on physics, values for the surface tension of water ranging from 73 to 81 dynes per centimeter at 20°C are found. The values in many cases the writer has found have been determined by one of the methods of measuring the force required to detach a ring or bar from the surface of the water. With this method zero contact angles between the object and the liquid are necessary, otherwise, low results will be obtained. For relative work these methods are satisfactory.

SURFACE TENSION BY THE FILM METHOD

The instrument is shown in Fig. 2. The knife edge to engage the liquid, can be made out of aluminum, copper, silver, platinum or other metal foil. It has been found that all of these metals, when thoroughly cleaned, have zero contact angles with water. The plate should be thin, not over .015 cm thick, and geometrically as nearly perfect with respect to the point of suspension as possible. The projections or horns *A* are to prevent the pulling of the liquid away from the ends of the edge and a correction has to be made for these as will be later explained.

The balance proper consists of a main support which is composed of tripod stand *B* and shaft *D*. To the latter is fastened the piece *C* that supports the swinging member E. The swinging member is a cork wheel about 2½ to 3 inches in diameter. Cork is used on account of its extreme lightness which adds to the sensitiveness of the instrument and because the axis on which it turns can be readily put through it. A steel bar 1½ mm in diameter passes axially through the cork, the ends of which are carefully ground to knife edges, and rest on steel or glass bearings. Around the periphery of the cork wheel is machined a small V shaped groove. Over the wheel and in this groove is hung a No. 50 silk thread (thread is used as its weight is negligible). To one end of the thread is hung the knife-edge which forms the liquid film. It must come down just below the graduated scale to be described later. To the other end of the thread is suspended a light aluminum pan into which enough fine sand is placed to just

balance the knife-edge and other weight at that end of the string. Into the periphery of the cork wheel is stuck a light aluminum pointer about .85 mm in diameter and of sufficient length to provide a weight a little more than sufficient to just balance the maximum tension that will come on the knife-edge. A pointer of this diameter and about eight inches in length will be deflected through about an 85 degree arc if a gram of weight is placed in

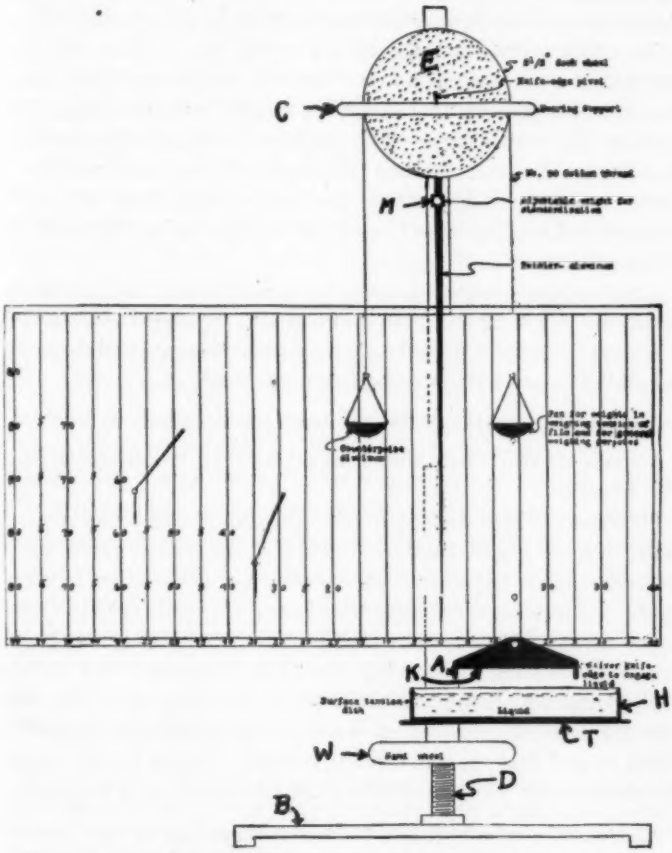


FIG. 2. Instrument for Measuring Surface Tension by the Film Method

the little pan on the knife-edge side of the spring. At the end of this aluminum pointer is hung a second very light and short aluminum pointer (about 1½ cm long and about .3 mm diameter) which hangs freely in a loop as shown. This secondary pointer maintains a vertical position through all angles of the main pointer.

The use of the secondary pointer obviates the necessity of graduating the arc of a circle, when the straight pointer is used, the divisions of which have to increase from the zero position of the pointer to a horizontal one, and makes the use of plain cross section paper as a scale possible. On this scale equal horizontal distances traveled by the secondary pointer represent equal tensions on the knife-edge. The secondary pointer which remains in a vertical position through all angles of the main pointer is easily read against the vertical graduation lines from the scale, low-powered reading glass is of assistance in reading the position of the pointer.

A part of the instrument not yet described is the mechanism for raising and lowering the dish[6] that contains the liquid to be tested. It consists of a table *T* and a sleeve which slides up and down on the shaft *D* when a thumb-wheel *W* is operated.

PROCEDURE IN MAKING A SURFACE TENSION MEASUREMENT

A single measurement which takes less than two minutes time is as follows:—

The liquid to be tested is placed in the dish *H* which has vertical walls. By the use of the thumb-wheel *T* the dish is raised until the knife-edge is pulled into the liquid. The dish is then lowered rapidly by turning the thumb-wheel until it is seen that the edge is just about to become detached from the liquid, from this point on (now watching the pointer) the dish is lowered very slowly until the pointer is seen to slip back a few divisions. The slip indicates that the column of water raised above the surface is letting go and that the film is being formed. This is the hydraulic column of water mentioned under the fifth method of measuring

[6] In the case of volatile liquids and with other liquids when the best results are desired, covered vessels are used. For general work this precaution is hardly justified.

surface tension which has to be corrected for in all methods using a ring or bar. For water and pure liquids the film lasts several seconds holding the pointer motionless at a given point on the scale. The tension is thus automatically measured. A film ½ inch long can sometimes be pulled out.

In making the correction[7] for the capillary rise of the liquid against the horns of the knife-edge which are actually dipping into the liquid at the time the tension in the film is being read, after the film has broken, the dish is again raised until the horns dip into it and until the surface of the liquid comes very close to the straight edge. The dish is then lowered a few turns. This is to insure a zero contact angle or to insure the same contact angle as existed at the time the film broke. The deflection resulting from the capillary action of the liquid on the metal horns which amounts to from two to four dynes depending upon the degree of wetting and the width and thickness of the metal horns should be subtracted from the first reading. The difference in the two readings, if the instrument is accurately standardized, is the surface tension of the liquid.

With volatile liquids measurements are made in closed vessels with a small opening through which the string, to which the silver knife edge is fastened, passes. No difficulty is experienced in forming films with volatile liquids such as benzene and alcohol.

If difficulty is experienced in forming a film for certain liquids practically the same result can be obtained by using a slightly thicker knife edge and by the same procedure as in the formation of the film with the exception that the plate is not pulled or detached from the liquid, but is pulled, by lowering the dish, until the pointer appears to remain constant through a turn or so of the thumb-wheel. At this point the lower edge of the plate is in the plane of the surface of the liquid and the question of the liquid in the portion *b* in Fig. 1 has been eliminated and we are

[7] The correction by dipping the horns into the liquid a second time may be avoided, by simply taking the reading for the film, and then allowing the pointer to come to rest after the film has broken, reading again and taking the difference. This procedure is less sure than the one described above.

weighing the tension in the films on either side of the plate which is equal to the weight of the liquid in the portions *a a*.

This is the procedure that was used in showing that the contact angle between the various metals mentioned earlier and water is zero degrees. This method calls for zero contact angles and we have never had to resort to it as films are usually easily obtained.

By this method the surface tension of water has been determined to be 72.8 dynes per centimeter at 20° C. This is in very close agreement with the most reliable figures so far obtained. This method checks well with the drop-weight and Jaeger methods, for all pure liquids tried.

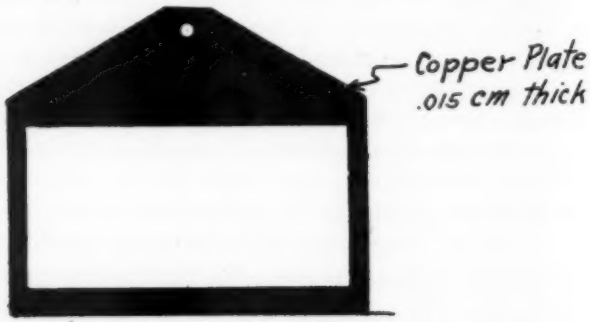


FIG. 3. A form of Frame used in Interfacial Tension Measurements

INTERFACIAL TENSIONS BY THE FILM METHOD

By the use of this instrument, the tension existing at a liquid-liquid interface can be almost as readily determined as for a liquid-air surface. A slightly differently constructed knife edge for forming the film is used. The design used is shown in Fig. 3.

The usual knife edge is removed, and the one shown here suspended in its place. It should be pointed out, however, that the knife edge or frame as used for interfacial tension measurements may be used also for surface tension work. A measurement is made as follows: If the interfacial tension oil-water, or benzene-water is to be determined, about 100 cc of water are put into a

beaker and on top of this is placed a layer of benzene or oil about 1/16 inch thick. The beaker with its contents as explained is put on the adjustable stand T which is raised by means of the thumb-wheel W until the knife edge, Fig. 3, has passed below the level of the interface, forming and pulling the oil film with it. The film formation is shown in Fig. 4.

The deflection of the pointer, which will be to the right on the scale is read before and after the breaking of the film. The difference gives the interfacial tension in dynes per centimeter. The same results are obtained whether the film is pulled from the water to the oil (water film) or whether it is pulled from the oil to the water. When a metal knife edge is used, it is better to go from the oil to the water as the oil more easily wets the metal plate. If it is desired to go from the water to the oil, the plate should be put in the water before the oil layer is added.

To measure the interfacial tension between water and a liquid heavier than water the same procedure is used. The oil should be first put in the beaker, and a shallow layer of water poured on top of it. The knife edge is allowed to pass through the water pulling a film of it into the oil. For measuring the tension at an interface between two liquids of equal specific gravity, the oil is placed in a smaller rectangular vessel which is set into the beaker and the water is poured around and over it.

METHODS OF STANDARDIZATION

In calculating the theoretical surface tension of a liquid the simple formula $Y = \frac{980 \times W}{2L}$ where W is the weight required to swing the pointer through the same number of divisions of the scale as 2 L cm of the film, where L is the length of the straight edge between the horns and Y the surface tension of the liquid.

The instrument is standardized to read direct in dynes per centimeter by raising or lowering the adjustable weight M on the pointer until a film of pure water swings the pointer just through 72.8 divisions of the scale. This requires several trial measurements. However, the instrument need not be actually standard-

FIG. 4. Showing Film Formation Stage in an Interfacial Tension Measurement

ized; the surface tension of water can be taken as 72.8 or for practical purposes 73.0 and a factor used.

Several thousand surface tension and interfacial tension determinations have been made with this instrument in studying the theory of flotation. It has been found that with oil-water emulsions it is the only instrument that will give true static surface tension, that is, surface tension at the point where equilibrium[8] between surface concentration and interior concentration exists. Most other methods measure the surface tension of relatively fresh surfaces and for emulsions give values from 1 to 15 dynes higher than that at equilibrium.

The instrument should find a wide application for general laboratory use and in institutions in the teaching of molecular physics for which it is eminently suited. It is simple of construction and the average operators can get consistent and reliable results with it. It is independent of contact angle and maintains perfect adjustment from day to day. It easily gives values reproducible to 1/10 dyne/cm. It works well on volatile liquids and measurements are conveniently made in atmospheres other than air. It is also convenient for measuring interfacial tension between liquids.

A brief description of this instrument and its application to one problem involving the study of surface tension was given in the August 13, 1921, issue of the Mining & Scientific Press, San Francisco, California.

The writer is greatly and pleasantly indebted to Mr. R. B. Elder of the School of Mines, University of Idaho, for his helpful suggestions, and assistance in checking the instrument against other methods; to Professor A. A. Knowlton of Reed College, Portland, Oregon, for his critical examination of the instrument, and to Mr. S. N. Shanfeld for his assistance in carrying out many of the experiments which have established the reliability of this method of measuring surface tension.

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[8] To maintain this equilibrium the emulsion must be circulated frequently. When the point of constant surface tension is reached, the emulsion will, on standing and without circulation, show either an increase or decrease in surface tension. The surface tension usually rises.

THE PASSAGE OF HYDROGEN THROUGH QUARTZ GLASS

By J. B. Johnson and R. C. Burt

SYNOPSIS

The *Rate of Flow of Hydrogen Through Quartz Glass* has been measured over the range of 300°C. to 900°C. Some measurements were also made with *Nitrogen and Argon*. A perceptible diffusion starts with hydrogen at about 300° C. and with the nitrogen at 600° C., and then in each case increases rapidly with the temperature.

A brief discussion is given on the *Possible Nature of the Flow* of gases through fused silica.

The heat resistive property of fused quartz has made this material valuable for the construction of many kinds of scientific apparatus. In some cases, however, its usefulness has been limited by the porosity to various gases at higher temperatures. O. W. Richardson[1] found that hydrogen and helium, and to a less extent neon, diffused through a quartz glass tube at 800°–1200° C. The rate of the diffusion has been measured when the pressure on both sides of the material was fairly high,[2] but the results thus obtained cannot safely be applied to high vacuum apparatus. The increased importance of electronic discharge tubes of larger power opens a new field for the use of fused silica, provided the material is used with proper regard for its limitation. The experiments to be described were therefore done to get more definite knowledge of the behavior of this material under conditions of high vacuum and high temperature. While the flow of hydrogen was studied more fully, some measurements were also made with nitrogen and argon.

The method used in making the measurements was to observe the pressure rise in an evacuated silica glass tube around which the gas flowed. A diagram of the apparatus is shown in Fig. 1. The furnace was an iron pipe around which was wound a heater of resistance wire and a covering of asbestos. A thermocouple

[1] Phil. Mag., *22*, p. 704; 1911.

[2] E. C. Mayer, Phys. Rev., *6*, p. 283, 1915; H. Wüstner, Ann. d. Phys., *46*, p. 1095, 1915.

placed near the center of the furnace was used to measure the temperature. The gas from a commercial tank was passed through the furnace at a slow steady rate at atmospheric pressure. The quartz glass tube Q was placed axially in the furnace and was connected to a vacuum pump, a McLeod gauge and a volume bulb V, the total volume of the system being about 1500 cc. A side tube T with a volume of about 3 cc could be immersed in liquid air for freezing vapors out of the system. The difference in level of the capillary mercury columns of the gage at the time of taking a pressure reading was kept less than the vapor pressure of water. No condensed water, therefore, existed in the closed capillary, so that when the side tube was not cooled the gauge indicated

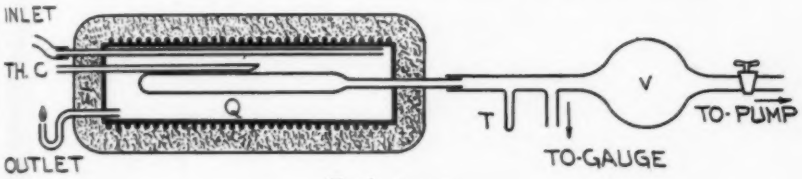

FIG. 1. Apparatus

approximately the total pressure, including that of water vapor. After the tube was pumped out the connection to the pump was closed during a run and the pressure read at short intervals while the temperature was kept nearly constant.

The materials tested were furnished by the Thermal Syndicate, Ltd., and were in the form of tubes 35 cm long, 1.5 cm in outside diameter and 1.5 mm wall thickness. Rough tests on several opaque varieties of fused silica, made from quartz sand, showed that these are unsuited for high vacuum apparatus even in the air at room temperature. The lowest rate of pressure increase observed was, for one of the tubes, about .001 mm of air per hour at room temperature and other tubes gave as high as ten times this value under the same conditions. The final work was therefore confined to the clear fused silica made from quartz crystals.

After the clear silica tubes had been heated up to drive off the vapors on the inner surfaces, no leakage of air or hydrogen at room temperatures was detected in as long a time as two weeks at a

pressure of less than .001 mm. Upon again heating the tube a measurable leak of hydrogen started first at about 300° C, and then increased rapidly with the temperature. Fig. 2 shows a summary of the results obtained with three tubes. R is the rate in cc per hour at which gas leaked into the tube per unit area, reduced to one mm pressure and room temperature, corrections being made for the temperature of the quartz and of the tube T.

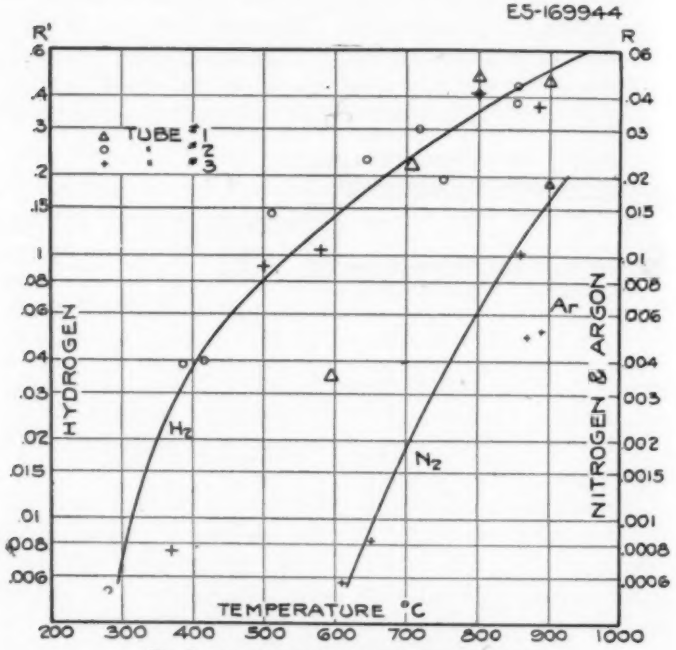

FIG. 2. Rate of Flow of Hydrogen, Nitrogen and Argon

The tubes were not quite of the same average thickness and the results have been reduced to correspond to a wall thickness of 1.5 mm, on the assumption that the leak is inversely proportional to the thickness. The runs with nitrogen and with argon are also shown in this figure. At 400° and 500° no leak of nitrogen as large as 5×10^{-4} mm was detected in 24 hours.

The result of changing from one gas to another is shown in Fig. 3, which makes clearer the difference between leakage of hydrogen and the heavier gases. The curve at the top of the figure gives the temperature of the oven during the course of the experiment. The upper pressure curve gives the total pressure in the system, while the lower curve gives the pressure of permanent gas measured when the small side tube was immersed in liquid air. The difference between the two curves represents the pressure of condensible vapors, about 90% of which was water vapor as was shown by exposing the gas to a small amount of

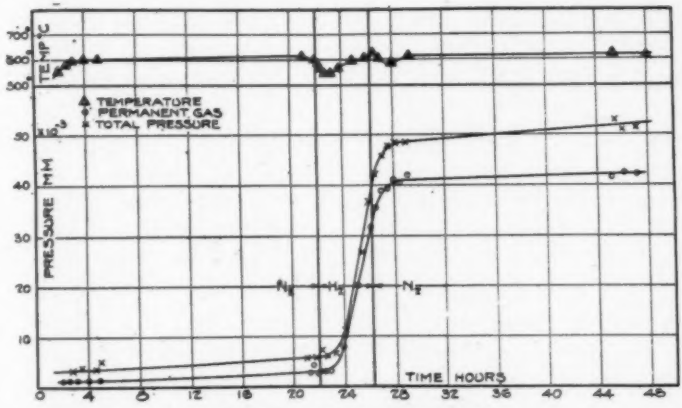

FIG. 3. Change of Gas Surrounding the Tube

phosphorus pentoxide. The presence of this condensible gas suggests the possibility that the rise in pressure was caused by gases continually given off from the walls of the tube rather than by a leakage through the walls, but the changes in slope show conclusively that there is a leakage of hydrogen at least. The constancy with time indicates that the lower rate of increase of pressure is caused by leakage of nitrogen as has been assumed and only to a small extent by release of gases from the inner surface of the tube.

The results of these experiments, though incomplete, justify a brief discussion of the nature of the flow of gas through fused silica. It seems improbable that a clear, dense substance such as

quartz glass is porous to gases in the sense that chalk is porous. It is equally improbable that in this inert material there is a chemical diffusion as in rubber. An assumption which might readily be made is that there is a flow of gas through very fine holes or tubes in the material. This view gains apparent support from the fact that even clear fused silica is not quite free from fine striations, caused by drawn out air bubbles, a condition which is so obviously present in the satin finish material. According to the kinetic theory, however, the volume of gas passing through a tube when the diameter of the tube is small compared with the mean free path of the gas molecules is inversely proportional to the three-halves power of the molecular weight and directly proportional to the square root of the absolute temperature. When the experimental rates for the three gases are compared, their ratios fall within the correct range for the molecular weight relation, but the increase of rate with temperature is very much greater than that shown by flow through tubes and apertures, and indeed varies as the third or higher power of the temperature, so that we must look for some other explanation than simple flow along capillary tubes. The transfusion begins at the temperature at which structural changes are known to occur in crystalline silica, and this fact suggests that the passage of the gas may accompany a modification in the structure of the non-crystalline material.

The data enable us to judge what to expect with tubes and bulbs of ordinary dimensions. The curves show that at the same outside pressure hydrogen passes through the walls about 100 times faster than nitrogen or argon. Under normal conditions, however, the hydrogen content of the atmosphere is small, about four parts in 100,000 by volume, so that in air the rate of admission of nitrogen should be of the order of 250 times larger than that of hydrogen. To take a concrete example which may be met with in practice, we can probably say that a well evacuated bulb of one liter capacity can be kept in the air at 400° C for one hundred hours before the pressure reaches 10^{-4} mm, and the transfused gas will be largely nitrogen.

RESEARCH LABORATORIES OF THE
WESTERN ELECTRIC COMPANY, INC.,
AND THE AMERICAN TELEPHONE AND
TELEGRAPH COMPANY, NEW YORK CITY.

A SIMPLE APPARATUS FOR COMPARING THE THERMAL CONDUCTIVITY OF METALS AND VERY THIN SPECIMENS OF POOR CONDUCTORS

By M. S. Van Dusen

The apparatus to be described here has been recently used by the author to measure the thermal resistance of various contacts between metals, either with or without the addition of some cementing material, and to compare the thermal conductivity of metals and thin specimens of poor conductors. The method consists essentially in comparing the temperature gradients in two materials placed in series, the rate of heat flow in each being the same. Heat flow in any direction other than that in which the

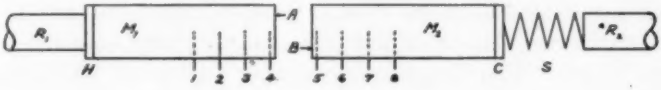

Fig. 1. Sketch of Apparatus

temperature gradients are measured as well as contact thermal resistances between the materials compared are made relatively small.

Fig. 1 shows a sketch of the apparatus as it has been used by the author, the particular object being to determine the thermal resistance of contact between metal surfaces under certain conditions. M_1 and M_1 are two solid brass cylinders, about 3 cm in diameter and 10 cm long, mounted coaxially. An electric heating unit H, consisting of a spiral of small copper tubing enclosing an insulated resistance wire, is soldered to one end of the cylinder M_1, and a water cooled cell C is placed on the opposite end of the cylinder M_2. Means are thus provided for producing a heat flow from H to C along the bars and through any material placed placed with the surfaces A and B. The rods R_1 and R_2 together with the spring S are used to apply a known force between the

surfaces *A* and *B*. Measurements of axial temperature gradient in the brass cylinders are made by means of the copper-constantan thermocouples (No. 36 wire) numbered 1, 2, 3, 8, inserted in 0.7 mm radial holes drilled 1.5 cm deep at definite intervals along the bars. Thermal contact between the thermocouple wires and the brass was improved by filling the holes with oil. It was found that under these conditions the depth of immersion was sufficient to eliminate the effects of lead conduction, no appreciable change in the temperature indication occurring when the junction was moved 1 cm away from the axis. The couples 4 and 5 are placed near the surfaces *A* and *B* so that the temperature of these surfaces can be found by extrapolation of the temperature versus distance curves along the axis of the system. A small amount of insulation on the two cylinders will serve to reduce heat loss from the convex surface to a very small value relative to the heat flow parallel to the axis. If now the surfaces *A* and *B* are put in contact, a constant current supplied to *H*, and a constant flow of water to *C*, temperature measurements after the steady state is attained will serve to compare the thermal resistance of the contact with that of a unit length of the brass itself. Similar experiments can be made with the surfaces cemented together by any means whatever. Furthermore the effects of pressure can be found by the means provided for varying the force holding the cylinders together. The influence of the character of the metal surface can be determined by roughening or grinding in various ways. It was found that if the surfaces were ground fairly flat, (convex with radius of curvature about 40 meters) the thermal resistance of a dry contact with a pressure of about 1 to 5 kg/cm² was equivalent to the resistance of from 1 to 1.5 cm of brass. When the surfaces were wrung together with water or a glycerine solution the effect of the contact could not be detected, being equivalent to less than 0.5 mm of brass.

This fact suggested that the apparatus could be used to compare the conductivity of various metals or alloys with some standard metal the conductivity of which is known. The heat flow would not be seriously distorted by the contacts. There is no difficulty in grinding the surfaces on a flat lap to a sufficient degree of flat-

ness. Cylinders of pure tin, lead, zinc, and 99.7% aluminum were prepared, each about 3 cm long and having the same diameter as the brass cylinders. The conductivities of these metals were compared at a mean temperature of about 40°C, the contact resistances being eliminated by the use of a dilute glycerine solution since pure water partially dries out on the hotter side in two or three hours. A specimen of brass cut from the same bar from which the apparatus was made was also compared, and no effect of the two contacts could be detected. Table 1 shows the results obtained, together with other values given in Landolt Bornstein tables. Zinc has been used as the standard and its conductivity has been assumed to be 0.265 cal sec^{-1} cm^{-1} deg^{-1}.

TABLE 1—*Comparison of Thermal Conductivity of Several Metals*

Metal	Thermal conductivity cal sec^{-1} cm^{-1} deg^{-1}	Probable best values at about room temp. taken from Landolt-Bornstein
Zinc (Standard).....	0.265	0.265
Aluminum (99.7%)	0.52	0.48
Tin.....	0.160	0.155
Lead.....	0.085	0.083
Navy Brass.....	0.28	.....

No great accuracy was anticipated when the apparatus was designed, but the results seem to indicate a precision within 5%. The variation of the thermal conductivity with temperature was disregarded, since it is within the experimental error in the small temperature range investigated.

The apparatus can be also used to determine the thermal resistance of very thin sections of poor conductors, such as mica, paper, etc., as well as thin films of liquids. In the latter case the brass cylinders are held a fixed distance apart by three very small mica separators, and the liquid remains between the ends of the bars by capillarity. The typical curves in Fig. 2 illustrate the general nature of the experiments, and in particular some results on wet and dry contact. The fact that the curves are sensibly straight and have the same slope on each side of the

break shows that the heat loss from the convex surface is negligible. The magnitude of the discontinuity in terms of the abscissa (i.e. distance along the axis) gives directly the thermal resistance of the contact or specimen in terms of centimeters of brass. Table 2 gives some results obtained with various contacts, as well as with layers of mica and paper. It will be noted that mica split into thin layers and subsequently squeezed together has a considerably greater thermal resistance than unsplit material.

TABLE 2—*Thermal Resistance of Miscellaneous Contacts or Thin Layers*

Nature of contact	Thermal Resistance in cm of brass	Pressure	Thickness of film	Remarks
		$\frac{kg}{cm^2}$	*mm*	
Dry	5.0	2.6	.....	Rough ground surfaces
Wet with water	0.2	2.6	.....	" " "
Dry	1.30	0.9	.....	Finely ground flat surfaces
Dry	1.15	2.6	.....	" " " "
Dry	0.85	4.4	.....	" " " "
Wet with water	0.10	0.9	.....	" " " "
" " "	0.00	2.6	.....	" " " "
Light mineral oil	0.20	0.9	.....	" " " "
" " "	0.10	2.6	.....	" " " "
" " "	2.05	.....	0.028	Spaced by 3 small mica chips
" " "	5.70	.....	0.066	" " " " "
1 layer mica	3.30	2.6	0.024	
2 " "	4.85	2.6	0.048	
3 " "	6.05	2.6	0.075	
4 " "	7.20	2.6	0.100	
5 " "	8.70	2.6	0.125	
1 " "	5.80	2.6	0.234	
1 " "	0.80	2.6	0.025	Wet with water
1 layer paper	13.5	2.6	0.103	
2 " "	27.0	2.6	0.205	
3 " "	38.0	2.6	0.310	
4 " "	48.5	2.6	0.412	

It is believed that this form of apparatus can be employed in schools, either in class room demonstrations or laboratory work.

The undergraduate student does not ordinarily obtain very clear conceptions in the subject of thermal conductivity, usually because he is not shown by actual experiment the analogy between electrical and thermal conduction. Experiments similar to the kind described in this paper follow closely certain experiments

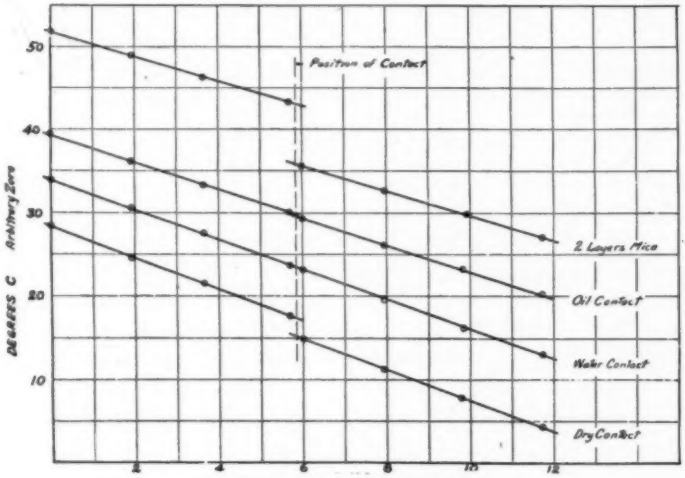

FIG. 2. Typical Temperature—Distance Curve

on Ohm's law which the student always performs in his first course in physics. Furthermore the student will obtain in a rather vivid manner correct ideas of the relative magnitude of various thermal resistances.

BUREAU OF STANDARDS,
WASHINGTON, D. C.
JULY 22, 1922.

AERONAUTIC INSTRUMENTS

By Franklin L. Hunt

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The instrument equipment of modern aircraft ordinarily consists of a group of ten or more instruments which are located on an instrument board in front of the pilot. They serve to assist him in the control of the altitude, speed and orientation of his aircraft and the behavior of the engine. In addition to the regu-

lar equipment special instruments are frequently installed, such as navigating instruments where long distance flights are to be made, experimental instruments for airplane performance tests, or instruments for military use. The purpose of this paper is to describe briefly the various types of aircraft instruments which have reached a state of practical development such that they have found extensive use in service.[1] These may be conveniently considered in the order mentioned above. A group of typical airplane instruments is shown in Fig. 1.

ALTITUDE INSTRUMENTS

Altimeters. Altimeters are used to indicate the altitude of aircraft. They are the same in principle as aneroid barometers and have as the essential working element a corrugated metal capsule from which the air is exhausted and which is maintained distended by an external or an internal spring. With decreasing atmospheric pressure, such as is experienced when an aircraft climbs, the evacuated capsule expands under the action of the spring. This motion which is very small, amounting to a few thousandths of an inch only, is multiplied by a suitable transfer mechanism and used to operate a pointer moving over a circular dial. The dial is graduated either in feet or in meters in accordance with some impirical mathematical relation between the atmospheric pressure and the altitude. The dial is rotatable so that the zero of the instrument can be adjusted for fluctuations in ground level barometric pressure. The pressure-altitude relation used in calibrating American altimeters is based on the assumption of a uniform air column temperature of 10°C and the corresponding mean humidity. It is calculated from the constants used in Smithsonian Meteorological Tables 51 and 54, 4th revised edition, and neglects the small effect due to the variation of gravity. It may be expressed by the relation

$$H = 62900 \log_{10} \frac{759.6}{P}$$

where H is the altitude in feet and P the barometric pressure in

[1] For a more detailed discussion see Reports No. 125–132, inclusive, of the National Advisory Committee for Aeronautics, 1922.

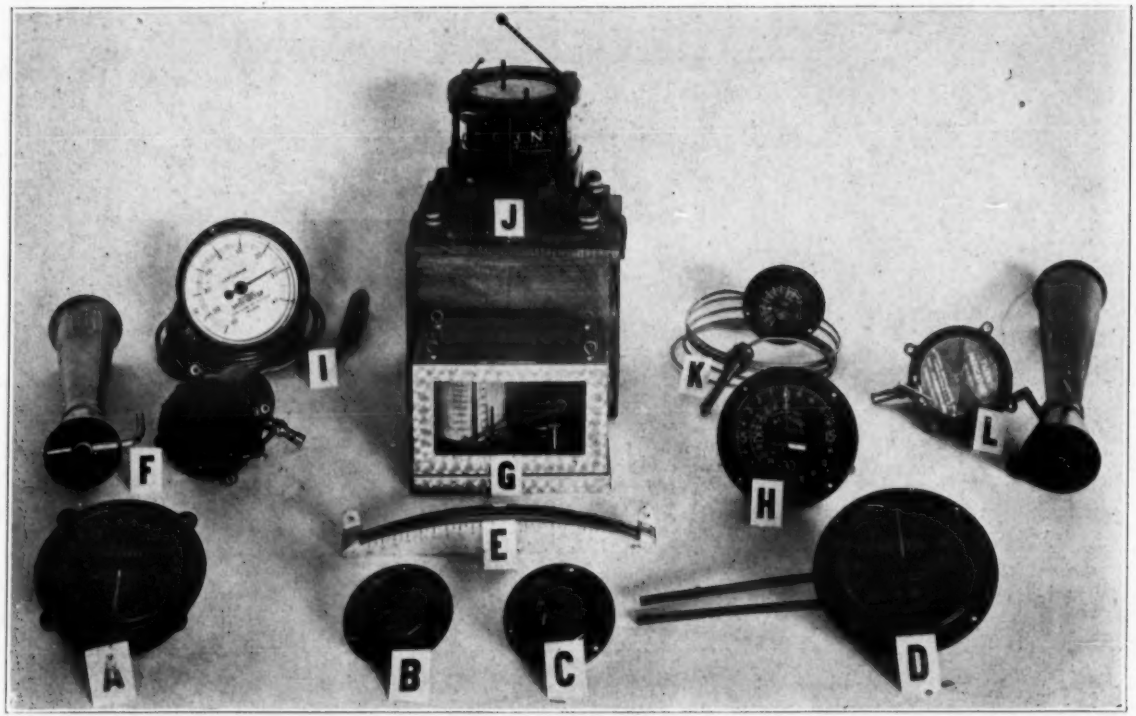


FIG. 1. AERONAUTIC INSTRUMENTS

A Tachometer, *B* Oil Pressure Gage, *C* Air Pressure Gage, *D* Airspeed Indicator, *E* Bubble Inclinometer, *F* Gyroscopic Pitching Indicator, *G* Barograph, *H* Altimeter, *I* Strut Thermometer, *J* Compass, *K* Radiator Thermometer, *L* Gyroscopic Turn Indicator.

millimeters of mercury. Practically the same formula is used in Great Britain. A typical altimeter is shown in Fig. 2.

Barographs. Barographs are the same in principle as altimeters but are provided with a recording mechanism which gives a continuous and permanent record of the altitude thruout flight. A battery of corrugated evacuated capsules is ordinarily used instead of a single capsule as in the altimeter, and interior springs are more frequently used than exterior ones. The expansion of the battery of capsules with decrease of external pressure operates

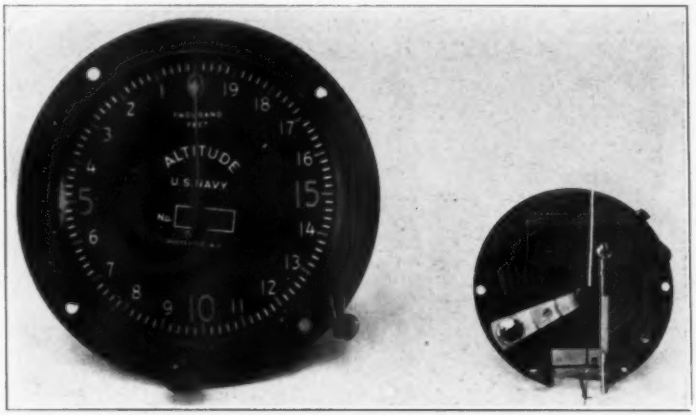


FIG. 2. Tycos Altimeter

a pointer which carries a pen and makes a record on a chart on a drum rotated by clockwork. The chart is graduated in feet or meters in accordance with some mathematical pressure-altitude relation, usually the same as that used on altimeters. Fig. 3 shows a typical aviation barograph.

Statoscopes. Statoscopes are used more frequently in lighter-than-air craft than on airplanes. They provide a sensitive means of indicating qualitatively whether an aircraft is rising or falling and help the aviator to maintain horizontal flight. The ordinary type consists of a closed air-chamber which is connected to the exterior air through a glass U-tube containing a

small quantity of colored liquid, thus forming a trap which seals the air in the container. Heat insulation is used to prevent the expansion and contraction of the confined air with changes of external temperature. When the aircraft rises or falls the pressure of the air inside the container becomes greater or less than that of the external air, according as the aircraft is ascending or descending, and the liquid in the trap which is visible to the avia-

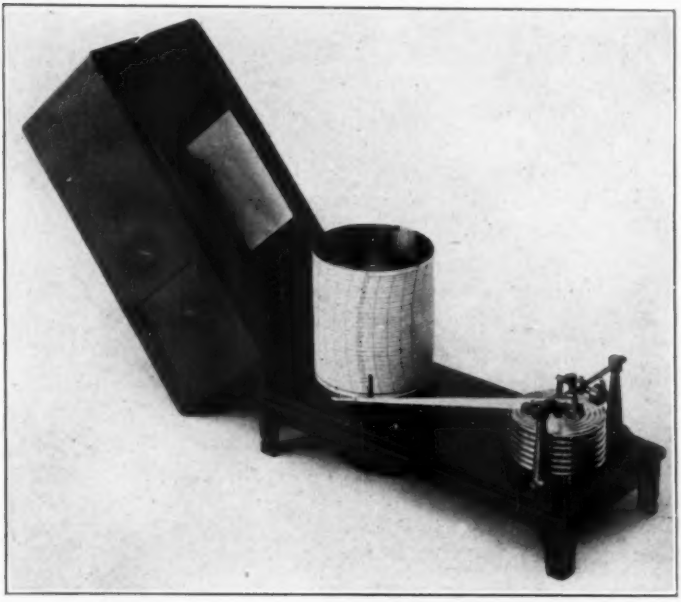


FIG. 3. Friez Barograph

tor is forced in one direction or the other, indicating a change of level. When the difference in pressure becomes sufficiently great equilibrium is re-established by air being forced past the liquid in the trap, after which the liquid again collects in the trap as previously. The frequency with which the air is forced past the liquid or as it is ordinarily expressed the rate at which the bubble

breaks is a rough measure of the rate of ascent or descent. Statoscopes can be made to detect changes in level of from five to ten feet. A typical instrument is shown in Fig. 4.

SPEED INSTRUMENTS

Air Speed Indicators. Air speed indicators show the speed of aircraft relative to the air. They give the speed with reference to the ground only in the absence of wind. The most commonly used types depend for their action on the pressure developed by the impact of the air stream caused by the motion of the airplane, or on the speed of rotation of small cup anemometers or air propellers. The indications of the pressure type are proportional to the density of the air so that the readings depend on the altitude. The anemometer type on the other hand shows practically no altitude effect. In the most usual form of the pressure type the pressures developed by a Pitot or Venturi nozzle located on one of the struts of the airplane is indicated by a sensitive gage on the instrument board. Usually it is also necessary to determine the static pressure at the point where the Pitot or Venturi nozzle is located. This is effected by using what is known as a static head which consists of straight tube closed at the end with a concentric ring of small holes or narrow slots at the sides. This tube is pointed in the direction of motion so that pressure within is maintained equal to that of undisturbed air without, the rush of air past the opening at the side of the tube being at right angles to these openings. Typical Pitot and Venturi nozzles are shown in Fig. 5A-B.

The indicator which is in effect a sensitive pressure gage ordinarily consists of one or more corrugated metal capsules enclosed in an air tight case or of an air tight case separated by a membrane of rubber or doped fabric into two air tight chambers. In early instruments a liquid manometer was sometimes used. The dynamic head of the pressure nozzle is connected to the diaphragm capsule and the static head to the air tight case, or in the doped fabric diaphragm type one head is connected to each of the air tight chambers. In some cases a combination of Pitot and Venturi nozzles is used to take advantage both of the pressure develop-

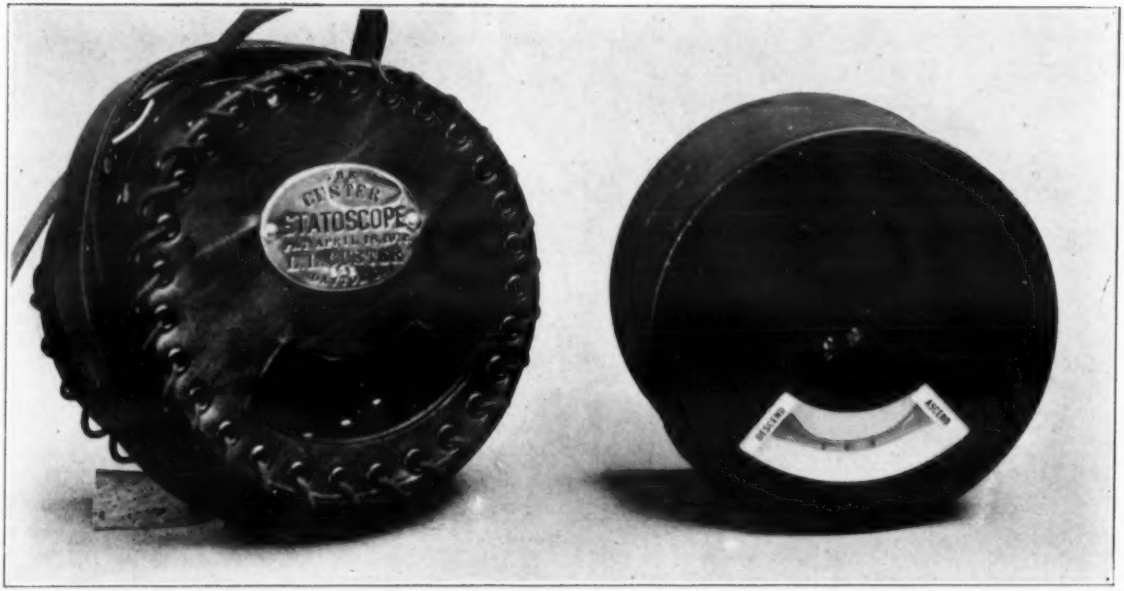


FIG. 4. Custer Statoscope

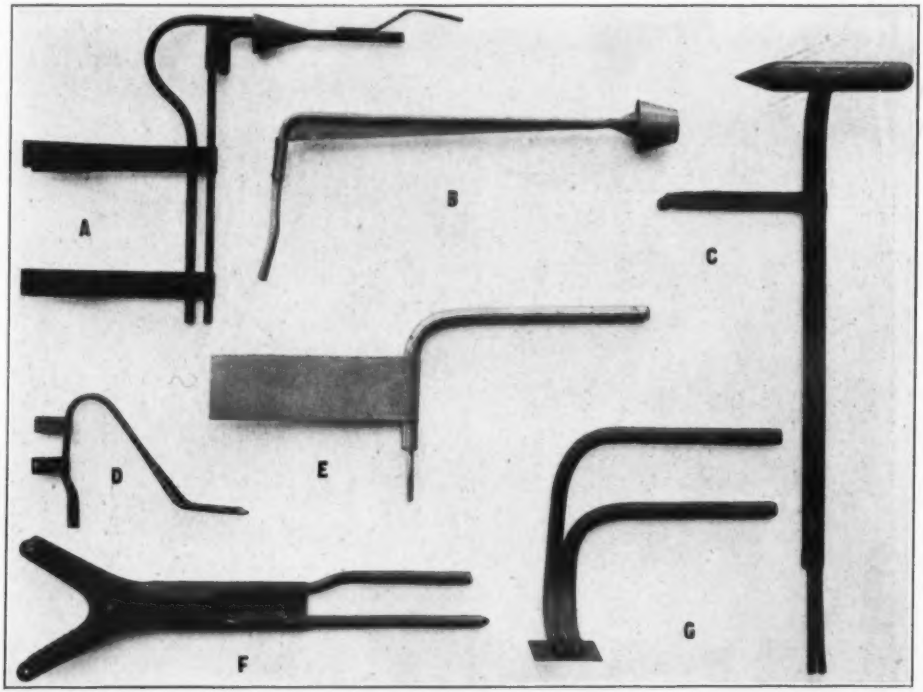


FIG. 5A. PITOT NOZZLES

A and *B* Nozzles with Static hoods, *C* and *E* Nozzles with concentric static heads, *D*, *F* and *G* Nozzles with separate static heads.

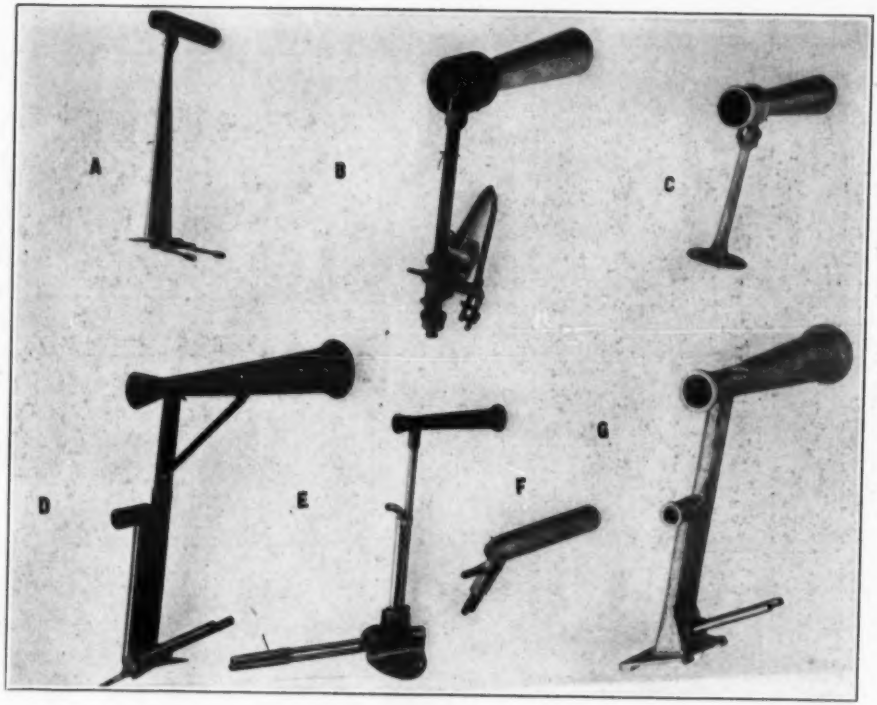


FIG. 5B. VENTURI NOZZLES

A, Single Venturi nozzle with concentric static head, *B* and *C* double Venturi nozzles, *D*, *E*, *F* and *G*, Pitot-Venturi nozzles

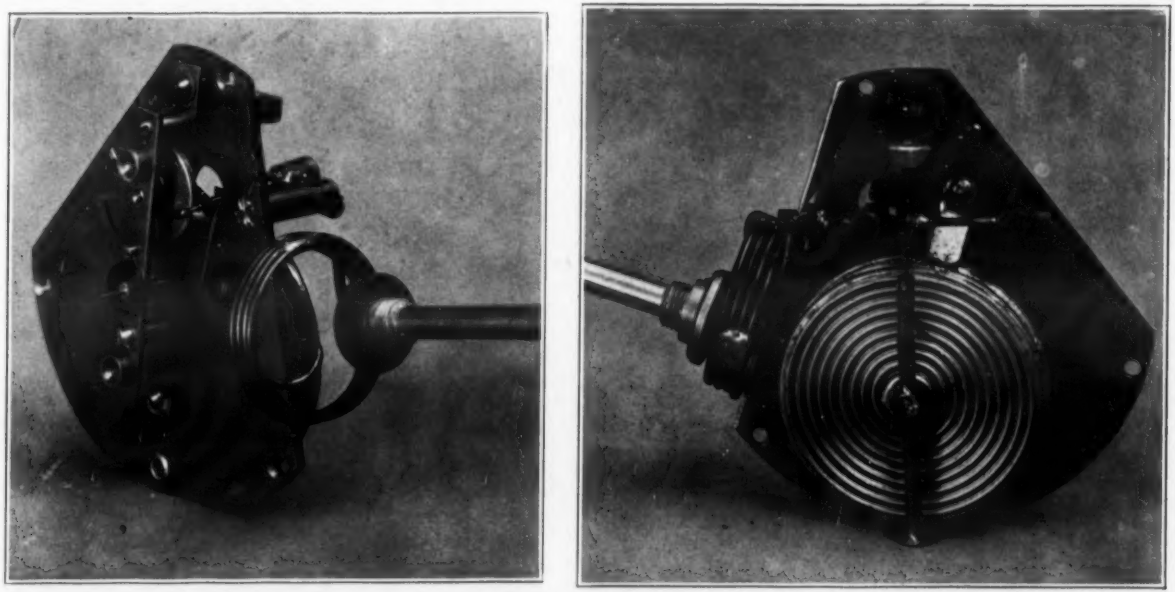


FIG. 6A. Bristol Double Diaphragm Air Speed Indicator

ment by the former and the suction by the latter. Under these circumstances no static head is used, the Pitot nozzle being connected to one of the air tight chambers and the Venturi to the

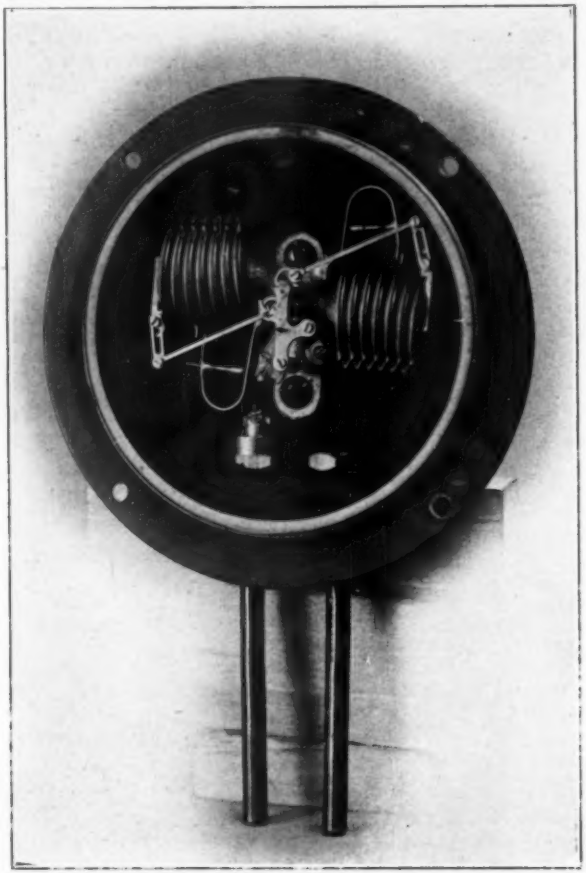


FIG. 6B. Foxboro Bellows Diaphragm Air Speed Indicator

other. The differential pressure developed by the nozzle causes the diaphragm to expand or contract according to the magnitude and direction of the excess pressure. This motion is carried by a

FIG. 6C. Ogilvie rubber diaphragm (above) Sperry single diaphragm (lower) Air Speed Indicators

suitable transfer mechanism to the pointer, indicating corresponding speeds on a dial which is graduated in miles per hour or kilometers per hour in accordance with the pressure-speed relation of the nozzle used. Most nozzles of the Pitot and Venturi type obey the so-called ρv^2 law, i.e., the pressure developed is proportional to the density of the air and the square of the velocity of motion.

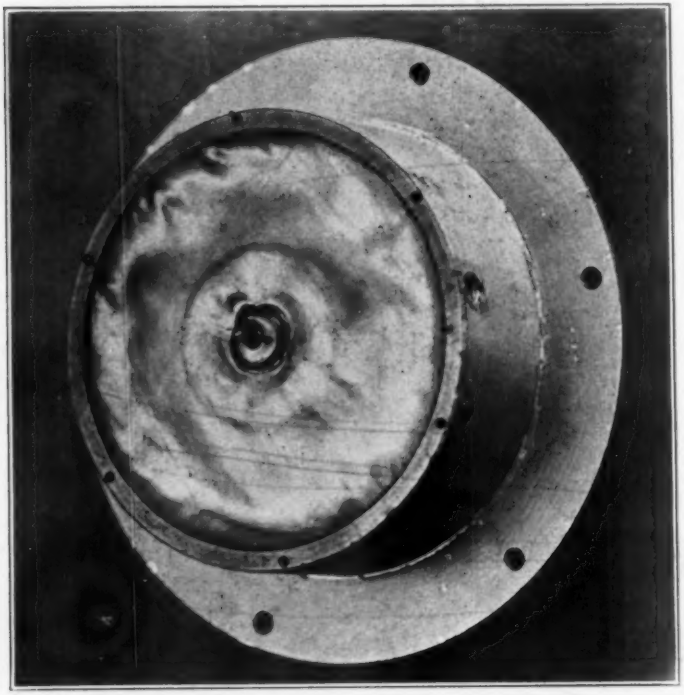


FIG. 6D. Clift Doped Fabric Diaphragm Air Speed Indicator

Typical air speed indicators of the Pitot and Venturi type are shown in Fig. 6A-E.

Instruments in which a flat plate perpendicular to the direction of motion is used to measure the air pressure have also been constructed. In these the plate is attached to a lever whose motion

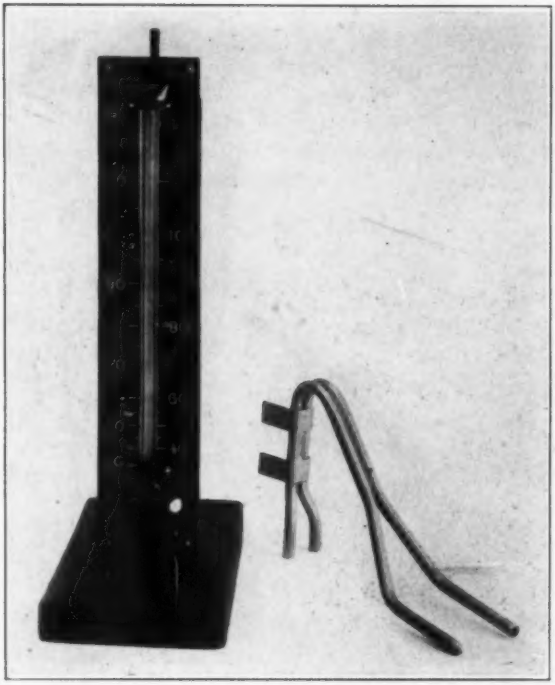


FIG. 6E. Pioneer Liquid Manometer Type Air Speed Indicator

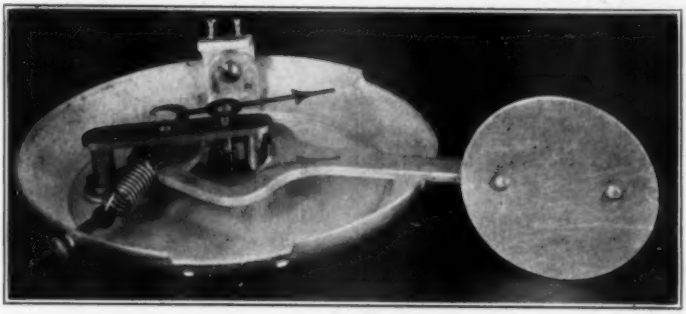


FIG. 7. Pensuti Pressure Plate Air Speed Indicator

is resisted by a spring. The displacement of the lever which depends upon the speed is used to indicate the air speed directly or it may be attached to a sector and pinion and a dial and pointer added. An instrument of this type is shown in Fig. 7. The pressure developed by these instruments also obeys the ρv^2 law.

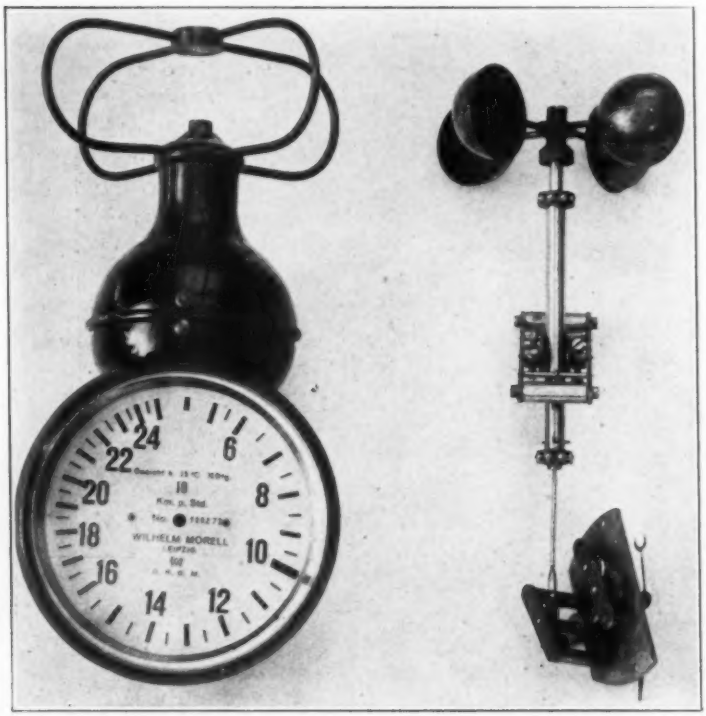


FIG. 8A. Morell Anemometer Air Speed Indicator

In instruments of the anemometer type the air speed is determined by the rate of revolution of a cup anemometer or air propeller. In most cases the rate of revolution is determined by attaching the rotating element to a centrifugal tachometer similar to that used in indicating the rate of revolution of the engine.

(See below). These instruments are ordinarily located on one of the struts of the airplane and are read from this position by the pilot. Instruments of the anemometer type with electrical distant control have recently been developed in which the anemometer alone is located on the strut. Wires lead from a specially designed commutator operated by the anemometer to the indicator which is on the instrument board. Typical anemometer air

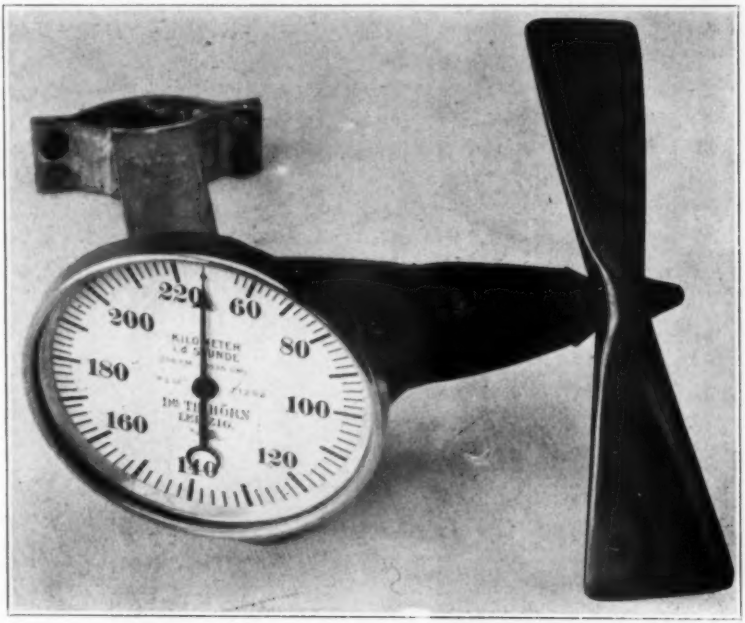


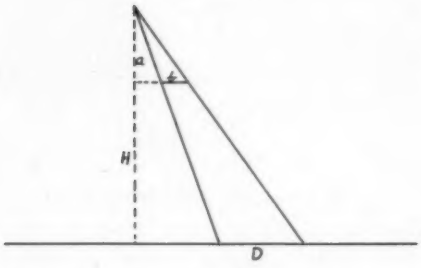
FIG. 8B. Horn Propellor Air Speed Indicator

speed indicators are shown in Fig. 8A-B. Hot wire anemometers in which the cooling effect of the air on an electrically heated wire grid have also been used to a limited extent but the device is complicated and not suited for ordinary use in determining the speed of the aircraft.

Ground Speed Indicators. The measurement of speed of aircraft relative to the ground is of importance in connection with

aircraft performance tests, long distance flying and military operations such as bombing. In case of aircraft performance tests the ground speed attained is ordinarily determined by flying the aircraft over measured courses or by sighting upon the aircraft from the ground with theodolites. These methods will not be considered in detail here, since we are primarily interested in the instruments carried by the aircraft itself. The methods of determining ground speed from the aircraft such as are used in long distance flying and in bombing are fundamentally either optical, dynamical, or electrical in principle. The actual instruments are still for the most part in an experimental state so only the methods of their operation will be considered here.

The simplest type of optical ground speed indicator depends upon determining with a stop watch the time for some object on the ground to pass between two sighting points in a horizontal line on the instrument. The ground speed can then be calculated from the separation of the two sighting points, the distance from the horizontal line defined by them to a third sighting point at the observer's eye, and the altitude of the aircraft. The principle may be demonstrated as follows:



Let a = distance from line b to the eyepiece.
H = the altitude.
b = distance between the two sighting points.
D = the distance traversed by the aircraft while the object on ground appears to move between the two sighting points.
t = time in seconds required.
S = speed of the aircraft.

Then

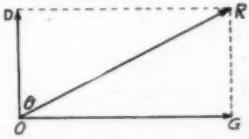
$$\frac{a}{H}=\frac{b}{D}$$

$$\therefore\ S=\frac{H}{a}\,\frac{b}{t}$$

$$=\text{const.}\ \frac{H}{t}$$

Another method is to use a rotating or reciprocating optical arrangement to neutralize the apparent motion of objects on the ground as seen through a telescope, or to cause a reference line in the telescopic field to move at the same rate as the image of the object on the ground. If then the rate at which the telescope or the image in the telescope field is moving is determined and the altitude of the aircraft is known the ground speed may be found. Several devices of this kind have been tried.

A modification of the last method is to introduce by means of a rotating telescope or similar device an artificial drift at right angles to the actual drift of the aircraft relative to the ground. From the direction of the resultant apparent drift and the magnitude of the artificial drift the ground speed can be computed. The principle may be illustrated as follows:



Let OG represent the ground speed of the aircraft the magnitude of which is to be found and the direction of which is shown by the use of a drift indicator, and OD the known artificial drift introduced at right angles to the ground speed OG by the rotating telescope or other device. Then OR will represent the resultant apparent drift as seen thru the rotating telescope and if the angle Θ between the artificial drift and the resultant apparent drift is measured the magnitude of the ground speed can be calculated by the relation

$$OG=OD\ \tan\ \Theta$$

Theoretically it would be possible to find the ground speed of an aircraft by determining the time integral of the accelerations to which it is subjected from the beginning of the flight. It has been proposed to do this by supporting a mass between springs

so that it is free to move in a horizontal plane in a fore-and-aft direction. The displacement of the mass under these circumstances will be proportional to the acceleration of the aircraft. If then the time integral of this displacement can be obtained mechanically and shown on a direct reading dial, the ground speed at any given instant will be known. Actually the inherent friction of the integrating mechanism and the inevitable accumulation of errors in integration make the device impractical. It is also necessary that the mass move only in a horizontal plane to prevent accelerations of the mass due to gravity. This can be brought about apparently only by gyroscopic stabilization which means much added weight and complication. No practical instrument of this type has been made.

Directional radio telegraphy has recently presented another possibility for ground speed measurement. With a directional receiving apparatus, the position of the aircraft with reference to two sending stations of known distance apart may be determined at successive time intervals and from these observations the ground speed computed. This is at present the only practical method of determining the ground speed of aircraft when the ground cannot be seen.

Rate of Climb Indicators. Rate of climb indicators are used to determine the component in a vertical direction of the velocity of aircraft. Like statoscopes they usually depend for their operation on the expansion or contraction of a volume of air confined in a heat insulated container. This container is connected to the external air through a fine capillary tube. When the aircraft rises the pressure of the air in the container becomes greater than that of the surrounding atmosphere owing to the lag in the pressure equalization caused by the capillary tube. The magnitude of the excess pressure is a function of the rate of climb. If then means is provided for measuring the excess pressure this can be used to indicate the rate of climb. The method ordinarily adopted is to make one side of the container a flexible metal diaphragm connected to an indicating mechanism or to connect to the container a U-tube filled with colored liquid. An instrument of the former type is shown in Fig. 9. Motion of the flexible dia-

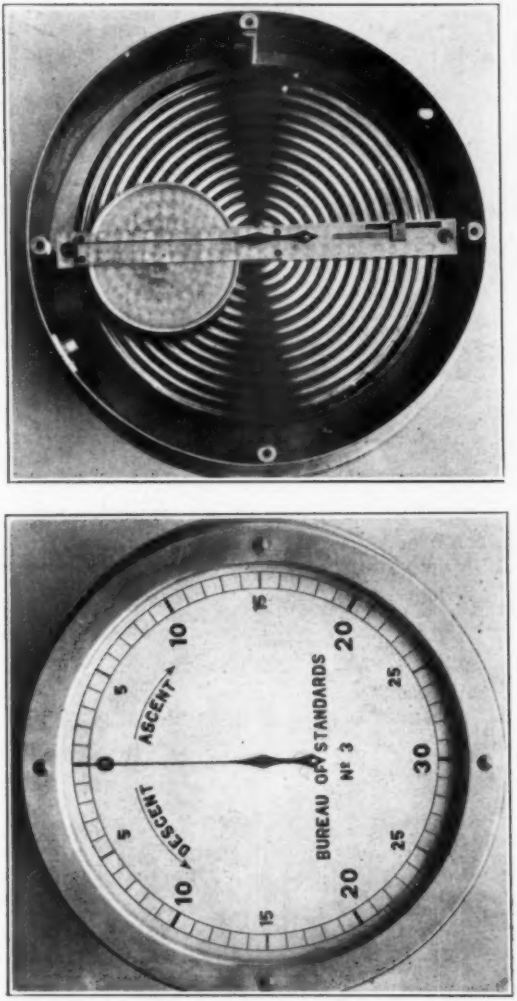


FIG. 9. Bureau of Standards Rate of Climb Indicator

phragm is multiplied by a system of aluminum pulleys and phosphor bronze strips and used to operate a pointer which moves over a dial graduated to indicate the rate of ascent or descent in feet per minute. An instrument of liquid manometer type is shown in Fig. 10. In this case the height of the liquid column is used as a measure of the vertical velocity.

ORIENTATION INSTRUMENTS

Compasses. The adaptation of the magnetic compass to use in aircraft presents serious difficulties because of the violent accelerations to which the instrument is subjected and also the unavoidable proximity of large moving masses of magnetic material in the aircraft. Liquid filled compasses are used almost exclusively because heavy damping is required. Aircraft compasses are in general quick-acting instruments with periods varying from 10 to 20 seconds. Compasses with longer periods are less disturbed by small transient accelerations but in general those with a period between the above mentioned limits are preferred especially when used in connection with turn indicators (see below) which have recently reached a practical state of development. Efforts have been made to overcome the unsteadiness and swirling of the liquid of airplane compasses by mounting the magnet and card in the center of a spherical bowl. Another method recently developed is to make the compass aperiodic by eliminating the ordinary card and mounting the needles on a light spider made of small straight wires projecting radially from the point of support in the damping liquid. Standard compasses of former types are shown in Fig. 11A-B and of the latter type in Fig. 12. Some are provided with both horizontal and vertical cards, others with inclined cards. The aperiodic compass dispenses with the card entirely and uses parallel wires on a rotatable bearing plate over the flat cover glass to sight on the needle.

The disturbing effect of masses of iron in the vicinity of the instrument board have led to an effort to develop distant reading compasses in which the compass proper can be located far away from the motor, for instance, in the fusilage, near the tail of the airplane, while the indicator is located on the instrument board.

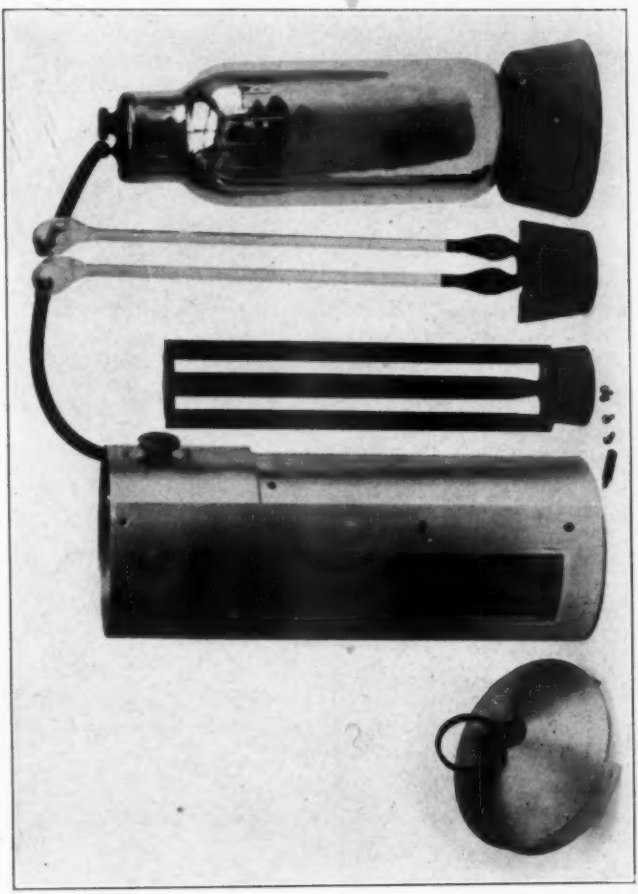


FIG. 10. Wright Rate of Climb Indicator

One method which has been tried is to use the current developed by a coil of wire rotating in the earth's magnetic field. This can be used to indicate direction since the magnitude of the induced current is a function of the orientation of the coil with respect to the earth. This device is known as an earth inductor compass.

FIG. 11A. General Electric Company Compass

Another method takes advantage of the change of resistance of selenium when exposed to light by providing two selenium cells located at diametrically opposite points above the compass card. Below each cell is an incandescent lamp. The card shields the

selenium cells to a greater or lesser extent according to the direction of the compass needle thereby changing the resistance of the selenium cells which constitute two arms of a Wheatstone bridge. This unbalances the bridge and indicates on a galvanometer on the instrument board the amount of displacement of the compass

FIG. 11B. Sperry Compass

card. This device is complicated and with its auxiliary attachments much heavier than an ordinary aircraft compass (See Fig. 13.)

Turn Indicators. Turn indicators are used to inform the aviator when he is deviating from a straight line course. The essential working element is a gyroscopic rotor which in accord-

ance with the principle of gyroscopic action tends to maintain its direction in space when the airplane deviates. The resultant relative motion is made evident to the pilot by the motion of a pointer connected to the rotor thru a lever system. The rotor is ordinarily driven either by the impact of an air stream on the serrated edge of the rotor itself or by making the rotor an induction motor. In the air-driven type the air stream is maintained by a

FIG. 12. Campbell-Bennitt Aperiodic Compass

Venturi tube which exhausts the air from the case in which the rotor is enclosed. Small orifices are provided in the case opposite the serrated edge of the rotor. Thru these the air streams in from outside the case impinging on the wheel and causing it to rotate. The electrical type can be connected to the storage battery which is a part of the standard equipment of modern aircraft, or it can

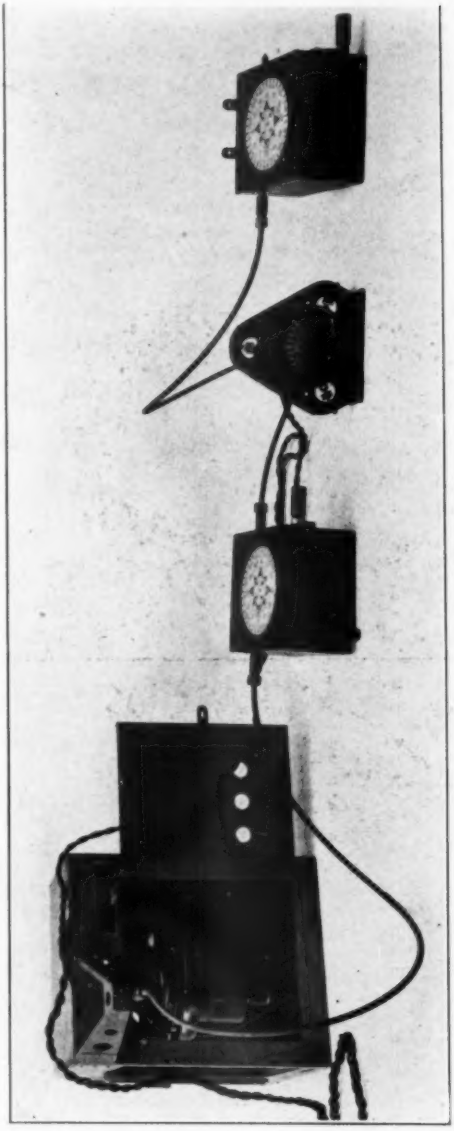


FIG. 13. Bamberg Distant Reading Compass with Indicator and Course Setters

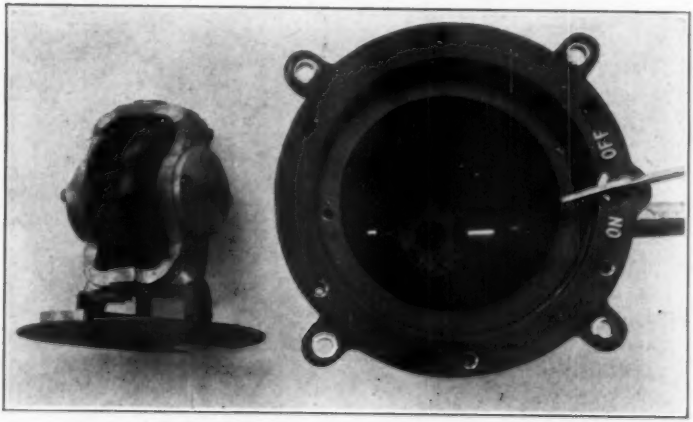


FIG. 14A. Sperry Air Driven Gyro-Turn Indicator

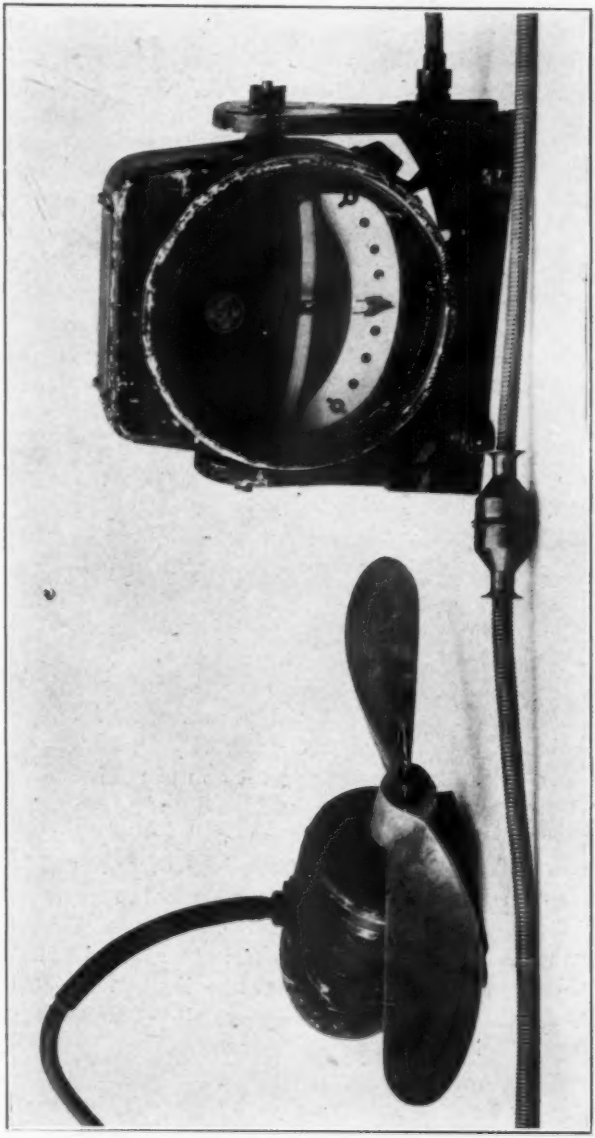


FIG. 14B. Drexler Electric Gyro Turn Indicator

be operated by a small auxiliary generator driven by a wind propeller. Instruments of both types have reached a practical stage of development and are an invaluable adjunct to the compass, particularly for use in cloud flying, since they can be made more sensitive to slight deviations than the compass and moreover function when the turn commences, at which time the compass is ordinarily temporarily useless because it is oscillating. Turn indicators of both types are shown in Fig. 14A-B.

Inclinometers. Inclinometers are used to indicate the inclination of aircraft with reference to the true vertical or to the resultant of gravity and forces of acceleration acting on the aircraft. There are two general types, those involving the principle of the liquid bubble level which indicate the aspect of the air plane with respect to resultant gravity and gyroscopic instruments which indicate the position of the airplane with reference to the true vertical. The former is much the simpler and more frequently used type. Representative inclinometers of liquid type are shown in Fig. 15A-F. These are designated by the name lateral and fore and aft inclinometers according as they refer to the condition of the airplane with reference to rolling and pitching. The liquid lateral inclinometer is essentially a curved glass tube filled with colored liquid in which a bubble forms. The displacement of the bubble indicates the inclination. The fore and aft inclinometer is the same in principle except that in this case it consists of a triangular shaped closed circuit of glass tubing partially filled with liquid. The liquid changes its level in the front arm of the circuit when the airplane pitches. See Fig. 15C. Liquid inclinometers of sector type are shown in Fig. 15D. In these a disk shaped receptacle with a circular glass face is half filled with colored liquid. The position of the surface of the liquid with reference to the normally horizontal diameter of the dial indicates the inclination of the aircraft. Liquid and air damped pendulum devices have also been used instead of instruments of the liquid bubble type. These are shown in Fig. 15E and F where 15E is a lateral inclinometer and 15F a fore-and-aft inclinometer.

An instrument of gyroscopic type is shown in Fig. 16. It is essentially a spinning top mounted on a pivot near its center of

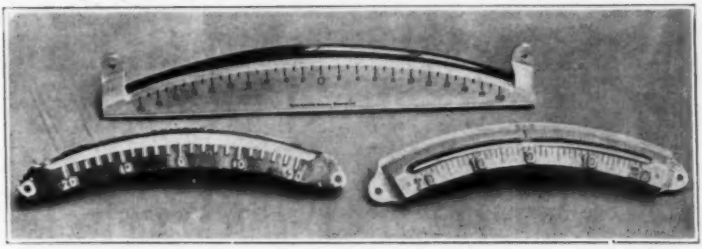


FIG. 15A. Liquid-Bubble Lateral Inclinometers

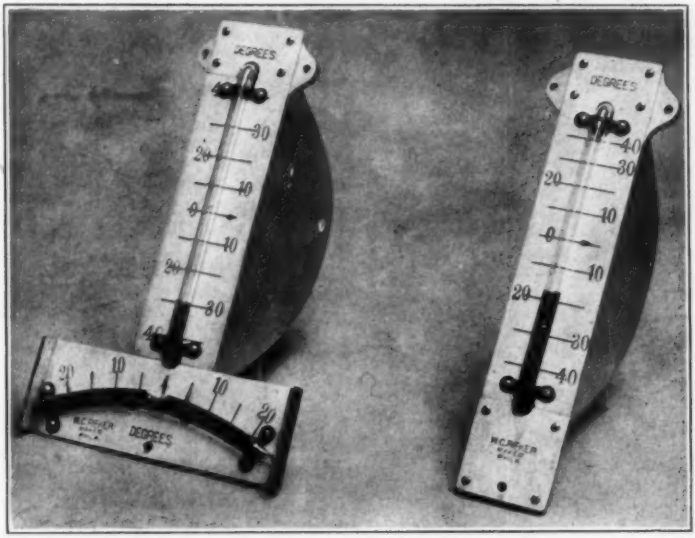


FIG. 15B. Ricker Liquid Fore-and-Aft Inclinometer and Combined Liquid Fore-and-Aft and Lateral Inclinometers

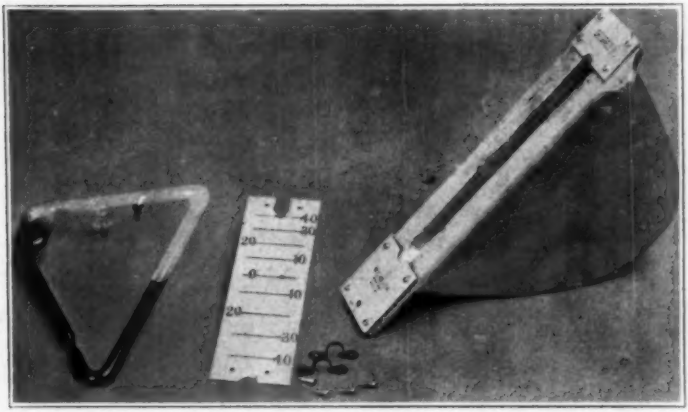


FIG. 15C. Ricker Liquid Fore-and-Aft Inclinometer—Disassembled

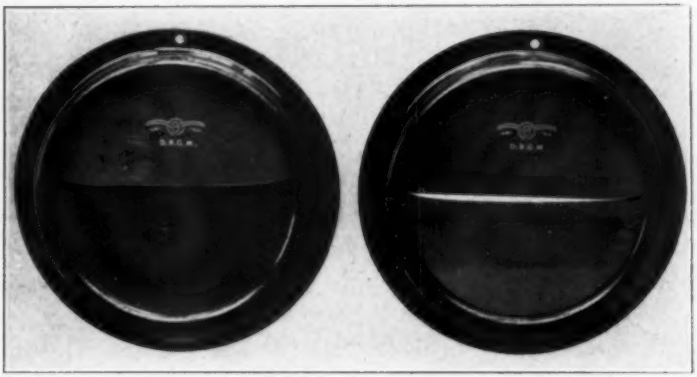


FIG. 15D. D.R.G.M. Sector Type Lateral Inclinometer

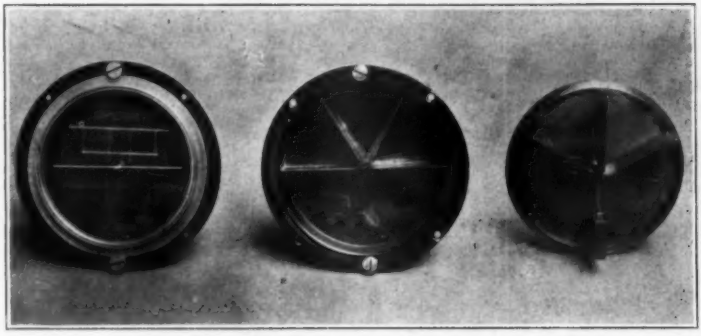


FIG. 15E. Sperry Pendulum Lateral Inclinometer

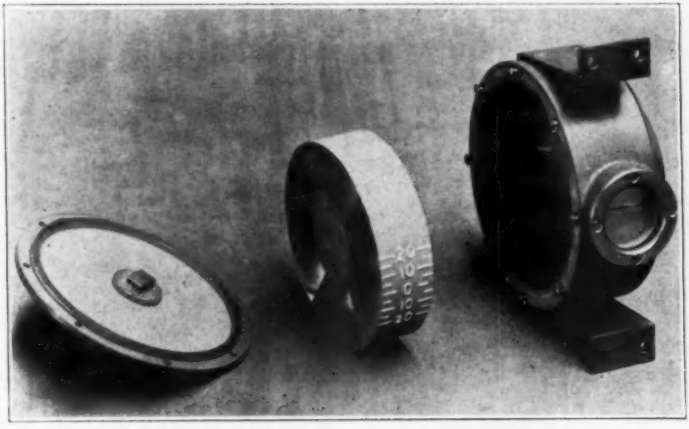


FIG. 15F. Sperry Pendulum Fore-and-Aft Inclinometer

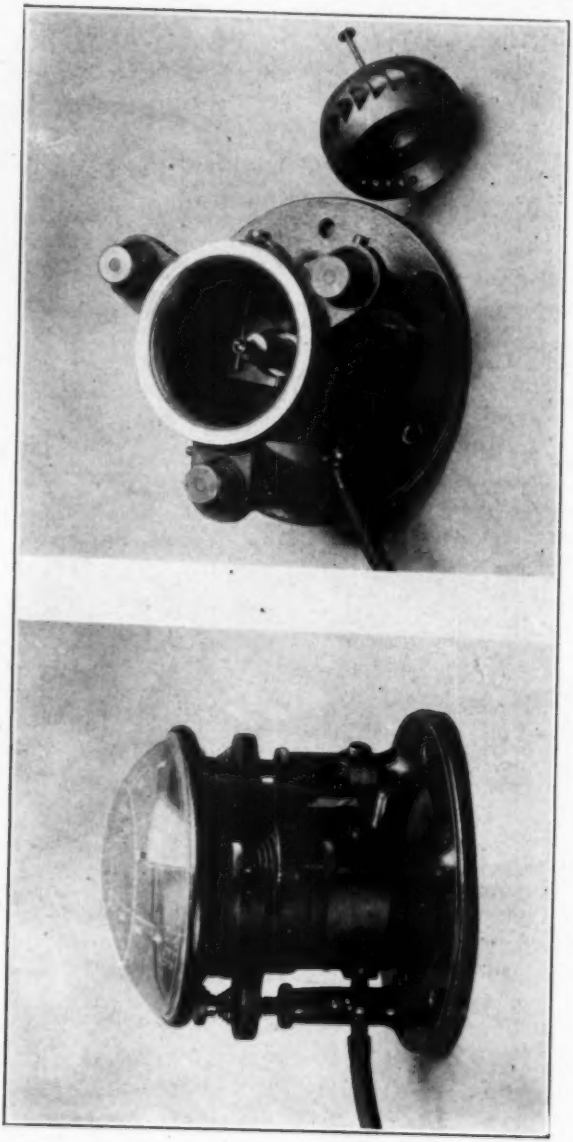


FIG. 16. Garnier Gyroscopic Top Inclinometer

gravity. It is rotated rapidly by an air stream impinging upon the serrated edge of the top. The gyroscopic action of the top tends to maintain its position vertical when the airplane pitches or rolls. The amount of displacement either laterally or longitudinally is indicated by the position of the pin of the top relative to the spherical cover of the instrument which is graduated in degrees. The power to drive the top is supplied by a Venturi tube which exhausts the air from the case and rotates the top as in the air-driven turn indicator described above.

ENGINE INSTRUMENTS

Tachometers. Tachometers are used to indicate the rate of revolution of the crank or propeller shaft of aircraft engines. They are usually driven by a flexible shaft which runs from the engine to the instrument board where the tachometer itself is located. The two types most commonly used are the centrifugal and the chronometric.

The centrifugal tachometer is the same in principle as the familiar ball governor and depends upon the tendency of a mass to move away from the axis of rotation under the action of centrifugal force. This tendency is resisted by a spring. The amount of motion which is a measure of the rate of rotation, is applied through a transfer mechanism to the pointer which moves over a dial graduated in revolutions per minute. A centrifugal instrument of standard design is shown in Fig. 17. In some centrifugal tachometers the centrifugal element consists of two or more small weights connected to the shaft by links as in Fig. 17, and in others of a single inclined weight which tends to assume a horizontal position under the action of centrifugal force. Centrifugal instruments are much simpler in construction and more durable than the chronometric type but are not so accurate as the latter.

In chronometric tachometers the speed is measured by the amount of motion of a toothed rack or gear system in a measured interval of time, usually one or two seconds, which is determined by a clockwork escapement. This motion is communicated to the pointer which is deflected in the given time interval an amount depending upon the speed of rotation of the driving shaft. The

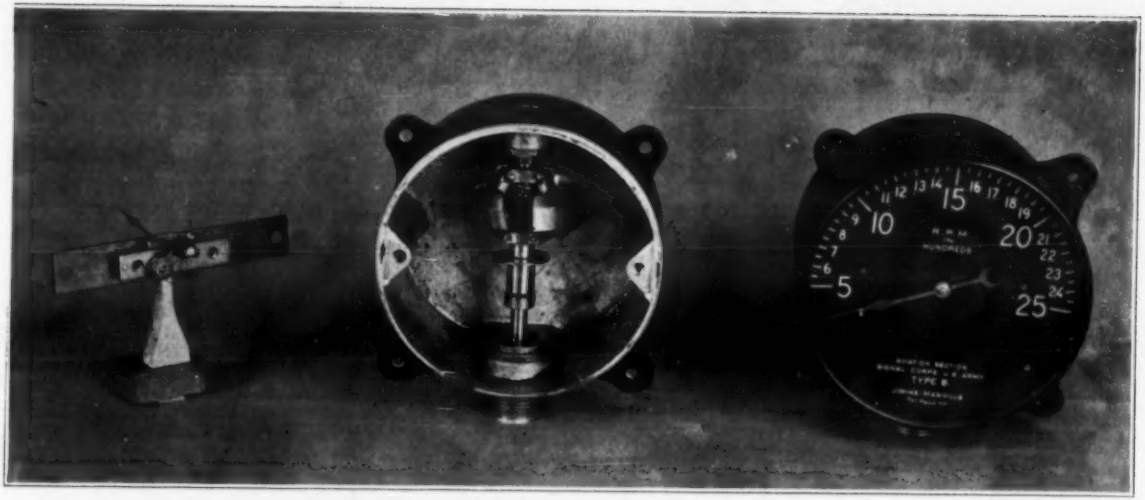


FIG. 17. Johns Manville Centrifugal Tachometer

mechanism is so designed that the pointer is locked in position during each succeeding time interval while the toothed rack or gears are in action. At the end of each time interval the pointer is released and suddenly jumps to its new position which is determined by the rate of rotation of the engine shaft during the time interval just ending. The result is that the pointer of the instrument moves by discontinuous jumps instead of continuously, as in instruments of the centrifugal type. A representative tachometer of the chronometric type is shown in Fig. 18. As stated

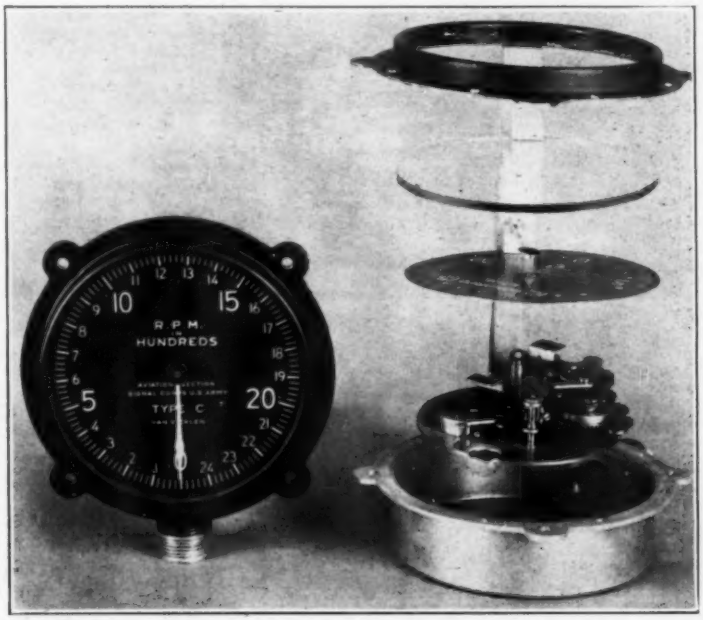


FIG. 18. Van Sicklen Chronometric Tachometer

above they are more accurate than the centrifugal tachometer but they involve complicated clockwork mechanism which easily gets out of order and is difficult to repair. However, a number of satisfactory instruments of this type have been made.

Several other types of tachometers have been used to a limited extent. Among these may be mentioned magnetic and electro magnetic tachometers, air viscosity and air pump tachometers. In the magnetic tachometer a permanent magnet is rotated near a conducting disk thereby dragging the disk, by virtue of the induced eddy currents, in opposition to a resisting spring an amount depending upon the rate of rotation. A pointer attached to the disk moves over a scale graduated in miles per hour. An instrument of this type is shown in Fig. 19.

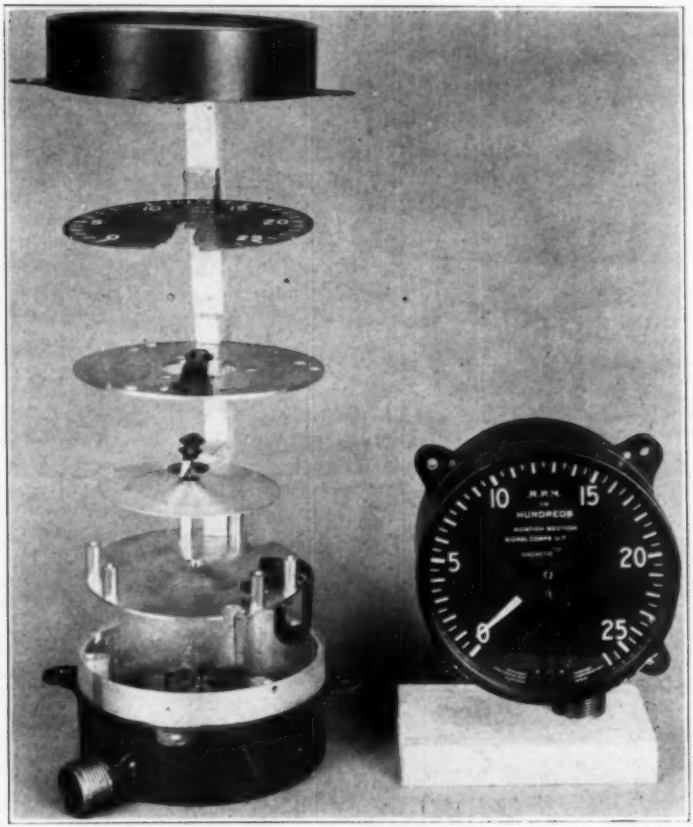


FIG. 19. Stewart-Warner Magnetic Tachometer

In the electromagnetic type a small magneto is attached to the engine shaft and connected to a galvanometer on the instrument board. The voltage developed by the magneto and hence the deflection of the galvanometer is proportional to the rate of revolution of the engine. The galvanometer is graduated to read in revolutions per minute. Magnetic and electromagnetic tachometers show larger errors than the centrifugal and chronometric type instruments and do not maintain their calibration as well.

The air-drag or viscosity tachometer consists of two concentric cylinders separated by a thin film of air. One cylinder which is attached to the engine shaft tends to rotate the other by virtue of the viscous action of the air film between them. This tendency to rotation is opposed by a spring. A pointer is attached to the second cylinder and the amount of deflection is a measure of the rate of revolution of the first cylinder. The deflection in this case however is not proportional to the speed. The temperature errors of these instruments are large.

The air-pump type consists essentially of an air pump which forces air into a chamber provided with a leak orifice. The pressure developed in the chamber depends upon the rate at which the pump, which is connected to the driving shaft, rotates. In escaping from the chamber the air deflects a vane whose motion is opposed by a restraining spring. The amount of the deflection of the vane is thus a measure of the speed of revolution of the driving shaft. Air-pump tachometers are subject to large altitude errors caused by the change in air density.

Pressure Gages. Oil and air pressure gages are used in aircraft to indicate the air pressure in the gasoline tank and the oil pressure of the engine lubricating system. Both gages are ordinarily of the Bourdon type but of different range, air pressure gages having a range of approximately 0 to 5 lb. sq. in. and oil pressure gages from 0 to 100 lb. sq. in. A group of representative oil and air pressure gages is shown in Fig. 20. The essential working element is a Bourdon tube, one end of which is rigidly attached to the instrument case and the other to the indicating system, which is either a sector and pinion or a system of levers. With increase of internal pressure the Bourdon tube expands, thereby causing the

pointer to move across the scale. In some of the instruments the pointer is concentric and in others eccentric, the advantage of the former being that it is given a much more open scale.

Gasoline Gages. Gasoline gages are used to indicate the depth of gasoline in the gasoline supply tank. The most common type consists of a float of cork, wood, or hollow metal which rests on the surface of the gasoline and which is connected to the indicating

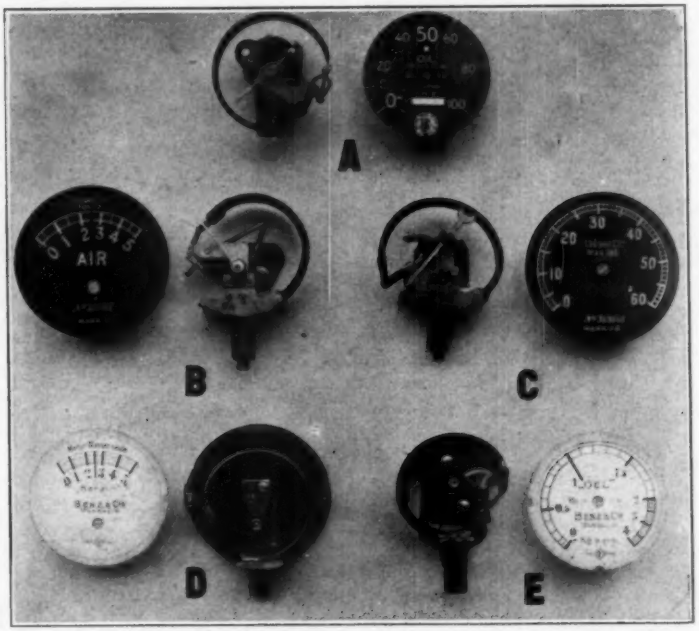


FIG. 20. Air and Oil Pressure Gages

mechanism by a metal rod or a flexible cord (See Fig. 21). Where it is possible to mount the indicator on the tank the float is allowed to travel up and down between two vertical fixed rods. A stiff twisted metal ribbon or inclined rod is rotated by the float as it changes its position, thereby operating the indicator which is mounted above the float and attached to the moving rod through

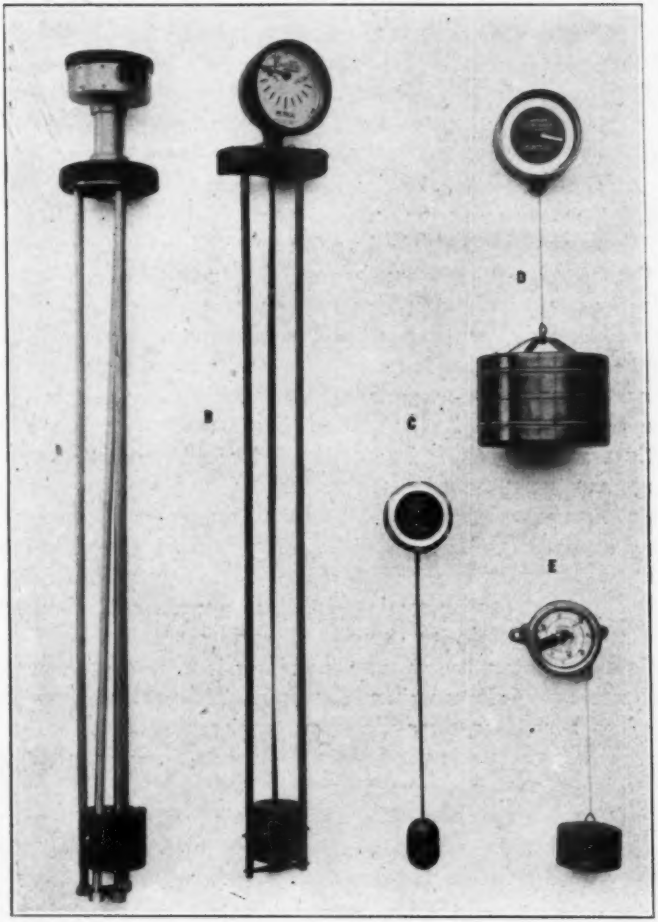


FIG. 21. Float Type Gasoline Gages

a system of gears. A disadvantage of this type of gage is that the float is likely to stick between the guide rods if they get out of alignment. Another method is that shown in Fig. 21 C, in which the indicator is mounted at the center of the side of the tank facing the aviator. In this case the float is attached to a long metal rod and rotates about the indicator. At the end of the floating rod is a small magnet which drags the iron pointer about as the float follows the level of the gasoline. Between the magnet and the pointer there is a metal disk which protects the cover glass from the hydrostatic pressure of the gasoline.

Float gages in which the float is connected to the indicator by a light weight silk cord, are shown in Fig. 21 D and E. The float consists of an air-tight, hollow, brass cylinder which moves up and down in a metal tube which reaches from the top to the bottom of the tank and whose diameter is slightly greater than that of the float. When the indicator is located at a distance from the float the connecting cord passes through a metal tube with roller fittings at the angles. The gage itself consists essentially of a drum on which the cord winds and unwinds and a system of gears which connects the drum to the indicating pointer. The cord is always maintained taut by a coiled spring which is attached to the drum. The indicator shown in Fig. 21D has a magnetically controlled pointer similar to that described above. One shown in Fig. 21E is provided with a spiral scale and by means of a rack and pinion mechanism the tip of the pointer is made to follow the convolutions of the spiral as it rotates. This makes it possible to allow the pointer to make several complete revolutions without confusing the indications.

Another type of gasoline gage which has been used to a limited extent depends upon the hydrostatic pressure of the head of gasoline in the tank. This pressure is measured by an indicator with corrugated flexible metal diaphragm capsules similar to those of an airspeed indicator. The gage is operated by connecting the case of the indicator to the air space above the gasoline tank and the diaphragm capsule to a tube extending to the bottom of the tank. Air is caused to bubble through the tube either by the use of a handpump or automatically by the use of a power pump

thereby impressing on the indicator a differential pressure equal to the head of gasoline. With this type of gage it is possible to have the indicator on the instrument board and connected to the gasoline tank by metal tubing. A disadvantage particularly from the military point of view, is that a rupture in the connecting tube is likely to cut off the fuel supply from the engine. A group of gages of this type is shown in Fig. 22.

Gasoline Flow Indicators. The rate of gasoline consumption in aircraft engines is found by the use of flow indicators. Typical instruments are shown in Fig. 23. In the one at the left of the figure a metal vane restrained by a coiled spring is deflected by the gasoline as it flows through the instrument. The gasoline flows past the vane in the space between the vane and the case. The case is provided with a cam surface which varies the space between the vane and the case as the vane rotates so that the deflection of the vane is made proportional to the rate of flow of gasoline. A pointer attached to the vane indicates the rate of flow in gallons per minute. In the indicator at the right the gasoline is forced out thru a slit in a vertical metal tube surrounded by a concentric glass tube. A small rider shown at the left floats on the gasoline. The height reached by the gasoline as it flows thru the slit and consequently the reading indicated by the rider is proportional to the rate of gasoline consumption.

Thermometers. Thermometers are used in aircraft to indicate the temperature of the radiator water and oil supply of the engine, the temperature of the atmosphere, and on lighter-than-air craft the temperature of the gas in the bags. The last two mentioned types are described below under Special Instruments. Thermometers for measuring the temperature of water and oil ordinarily consist of a metal bulb partially or completely filled with liquid which is located at the point whose temperature is to be determined and which is connected by means of a capillary tube to some form of pressure gage, usually of the Bourdon type, located on the instrument board. Two types of pressure thermometers are used. These are known as the vapor pressure and liquid filled type, according as they depend upon measuring the variation of the pressure of the vapor of a volatile liquid or the expansion of a

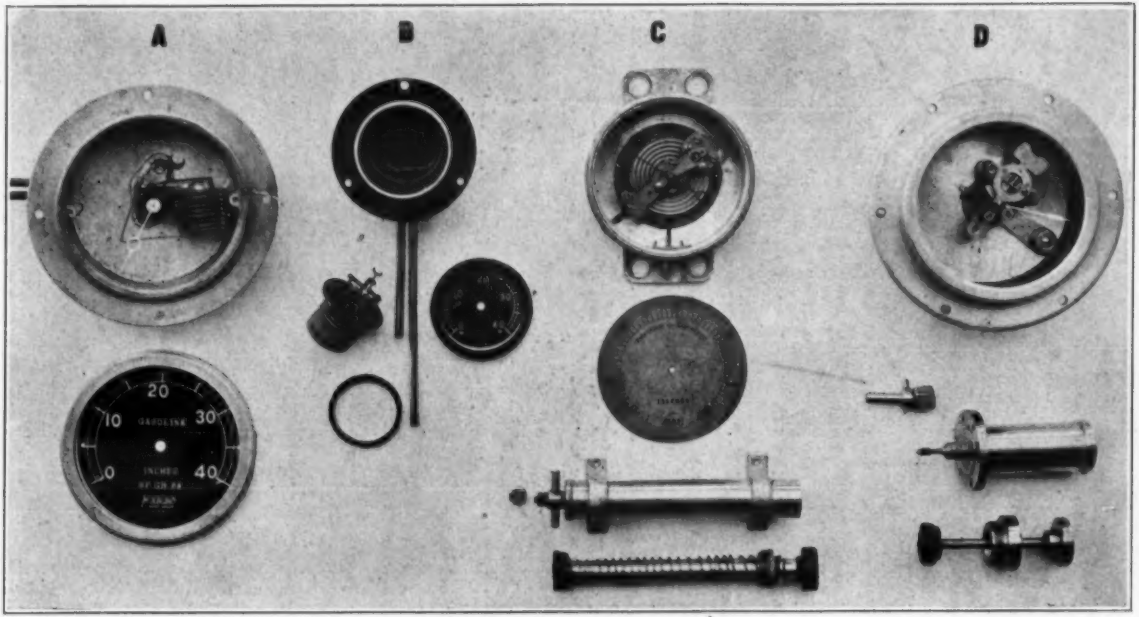


FIG. 22. Pressure Type Gasoline Gages

liquid with change of temperature. In the former case the bulb is only partially filled with liquid and the connecting capillary tube and gage is filled with vapor, while in the latter case the entire system including the bulb, capillary tube and gage is completely filled with liquid under pressure. Ethyl ether and methyl chloride are the most frequently used as the volatile liquid. Ethyl alcohol is the liquid usually used in the liquid filled type. The vapor pressure type is affected by changes of altitude. The liquid filled type on the other hand, gives erroneous readings if the temperature of the gage and the capillary tube differ from that at which the instrument was calibrated. Typical thermometers of both types

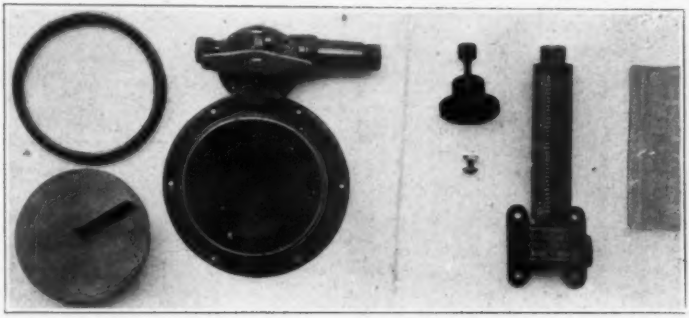


FIG. 23. Gasoline Flow Meters

are shown in Fig. 24. The vapor pressure instrument has an ordinary Bourdon tube which is connected to the indicating mechanism by a sector and pinion, such as that used in the pressure gages previously described. The liquid filled thermometer has a coiled Bourdon tube with several convolutions. It is also provided with a bimetallic temperature compensator which is connected between the Bourdon tube and the indicating mechanism.

NAVIGATING INSTRUMENTS

The use of aircraft for long distance flights over both land and water and for night flying has required the development of aerial navigating instruments. The methods applied are fundamentally

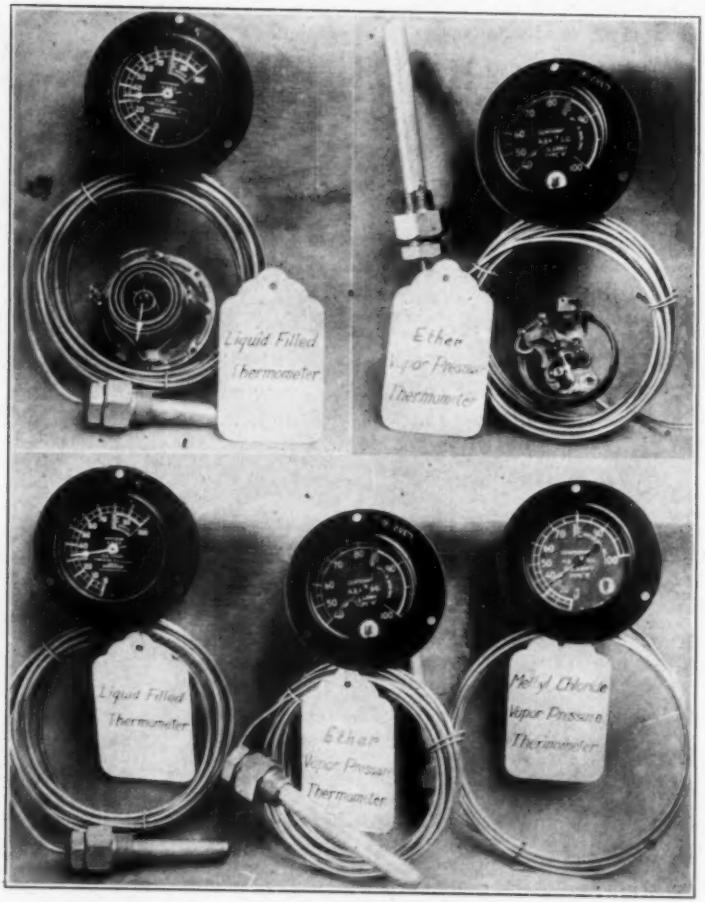


FIG. 24. Liquid and Vapor Pressure Thermometers

the same as those used in the navigation of ships at sea, the most important difference being the necessity of adapting the instruments to the relatively swift and unstable aircraft and, also, the uncertainty introduced by swift air currents which change rapidly in magnitude and direction, not only with time but also with altitude. It has thus been found impracticable to chart air currents as is done in the case of ocean currents at sea.

The simplest method of air navigation is that in which maps of the territory traversed are used and the course is guided by following landmarks known to the pilot. More general methods which involve calculating the course of the aircraft are (1) dead reckoning in which position at a given time is calculated from a previous known position by determining the direction of flight and speed with reference to the earth, and (2) astonomical observations in which the altitude or azimuth of the sun or stars is measured and the position computed from the Greenwich siderial time, the equation of time and the position of the sun or stars. Still another method recently developed is the use of the radio direction finder in which the position is determined with reference to radio stations by the use of a radio direction finder on the aircraft.

Maps and Charts. When maps are used they are frequently mounted on rolls in a map case (See Fig. 25A) so that a number of maps can readily be made accessible. Sometimes the map is mounted on a board and protractors and parallels provided for convenience in locating directions and measuring distances. Such a device is shown in Fig. 25B.

Dead Reckoning Instruments. The factors involved in the method of dead reckoning are the direction of the aircraft as determined by a compass, the air speed, the ground speed, and the drift with reference to the earth. Instruments used in making the first three measurements have already been discussed in this paper. Drift indicators usually depend upon determining by sighting wires or parallel lines in the instrument or in the focal plane of a telescope the apparent direction of motion of objects on the ground or on the water or even of the waves of the sea whose motion is so slow compared with that of the aircraft that it can

be neglected. Instruments of this type known as drift bearing plates are shown in Fig. 26. These consist of a rotatable graduated circle with diametral sighting wires which are turned parallel to the direction of drift. The vertical attachment is used in determining the ground speed and carries an eyepiece which is adjusted for altitude by the graduated scale on the attachment.

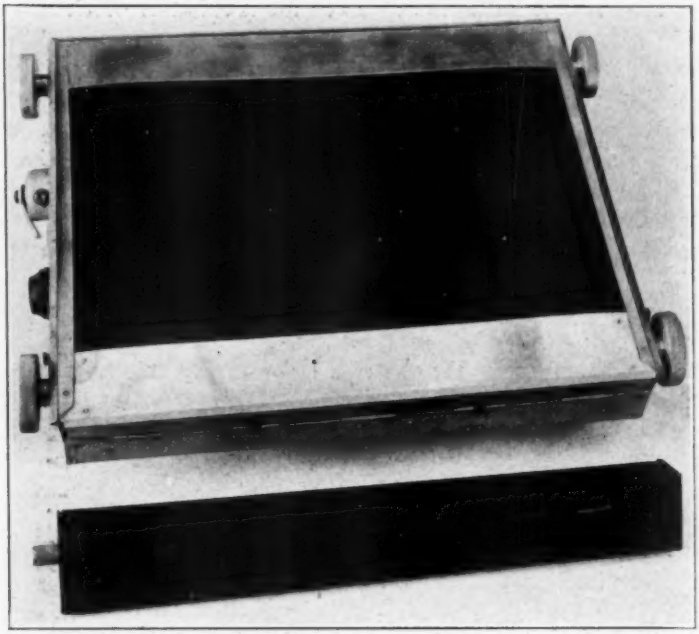


FIG. 25A. Map Case

The ground speed is determined by finding with a stop watch the time required for an object on the ground to pass between two ball sights on the instrument. A more complicated device with attachment for adjustment of the lubber-line of the compass is shown in Fig. 27. In this case the direction of drift is determined by adjusting a system of parallel lines in the focal plane of the

telescope, shown at the left of the figure, to the direction of drift. This automatically changes the position of the lubber-line of the compass.

The drift indicator shown in Fig. 28 in addition to determining the direction of drift and the ground speed has adjustments which

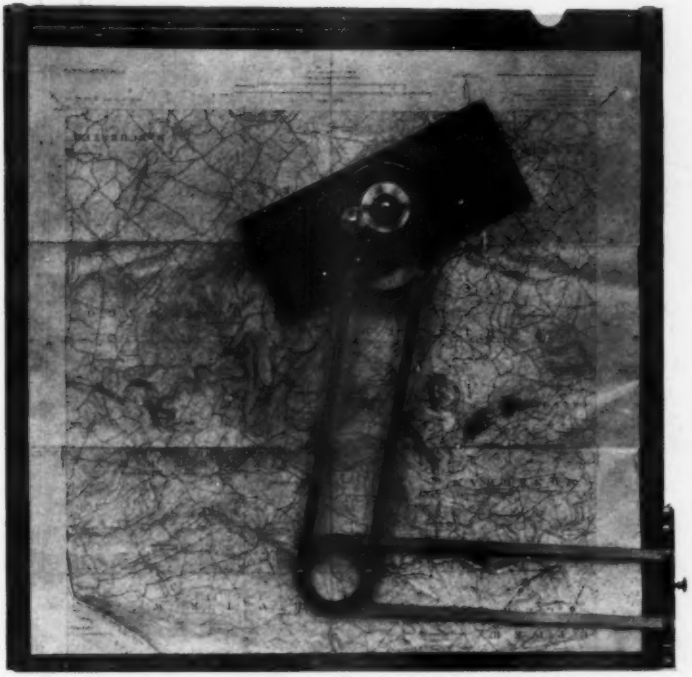


FIG. 25B. Bigsworth Chart Board

when the instrument is also set for the airspeed automatically determines the magnitude and direction of the prevailing wind, or as it is ordinarily expressed, solves the velocity triangle. The ground speed is determined as in the drift bearing plate just described by placing the eye at the eyepiece and noting the time

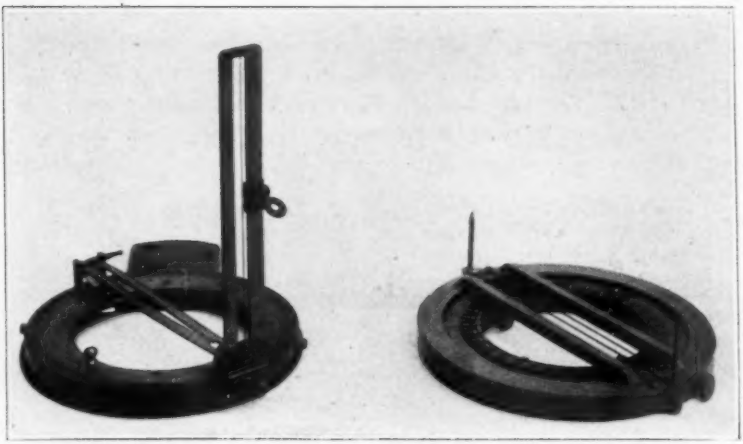


FIG. 26. Drift Bearing Plates

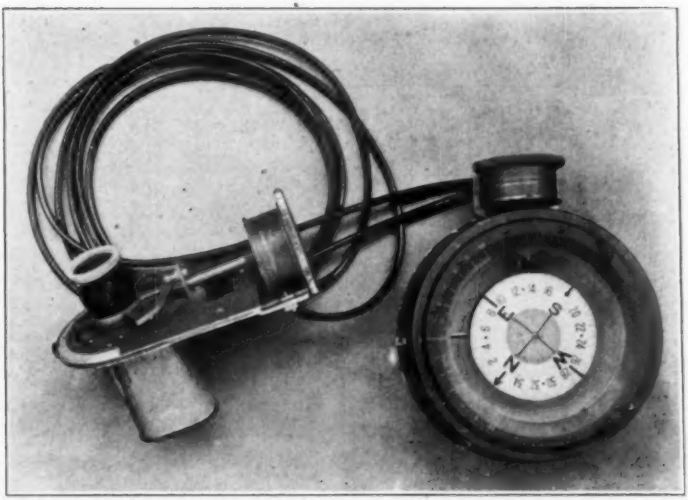


FIG. 27. Sperry Synchronized Drift Set

required for an object on the ground to pass between two points on the sighting arm.

The device shown in Fig. 29 is a synchronized drift sight which determines the wind vector from the direction and magnitude of drift and the air speed. The repeater which is attached to the main instrument indicates the result to the pilot. The unique feature of this device is the method used to determine the drift. An object on the ground is followed by means of the telescope at the right of the figure and a series of points plotted on the paper by depressing the pencil which is maintained parallel to the

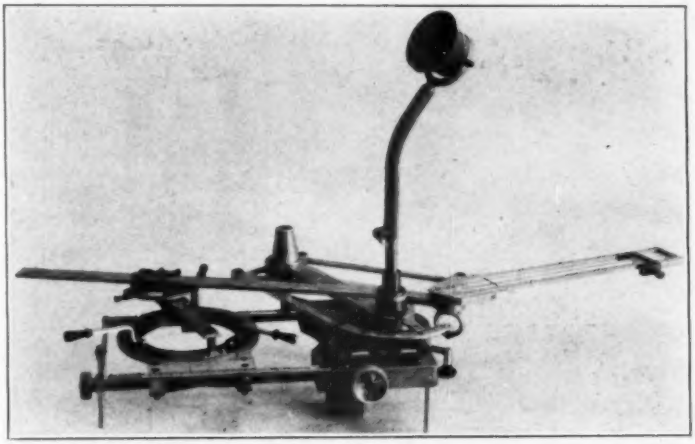


FIG. 28. Crocco Drift Indicator

telescope by a lever system. A series of points showing the direction of drift is thus obtained, defining a line in which the irregularities of the individual observations due to the rolling and pitching of the aircraft are eliminated.

A number of simple devices have been invented to aid in solving the velocity triangle. Three of these are shown in Fig. 30. They are used by setting the adjustable arms in the direction of the two known velocities of the velocity triangle, setting the adjustable sliders for the magnitude of these velocities and rotating the

disk until the arrow on it is parallel to the line through the two sliders. The direction of the arrow is the direction of the third velocity component. Its magnitude is determined from the scale on the disk by the distance between the two adjustable sliders.

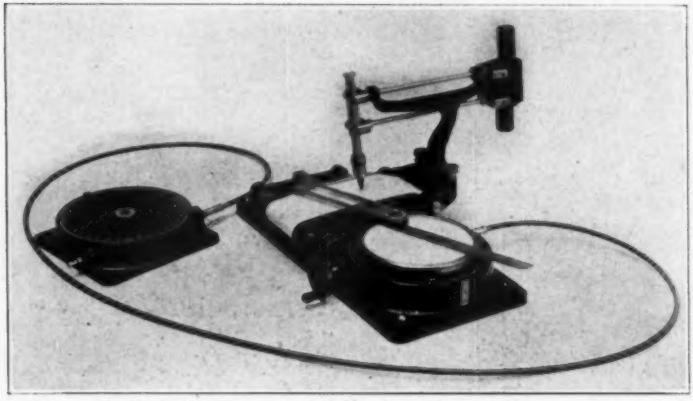


FIG. 29. Le Prieur Navigraph

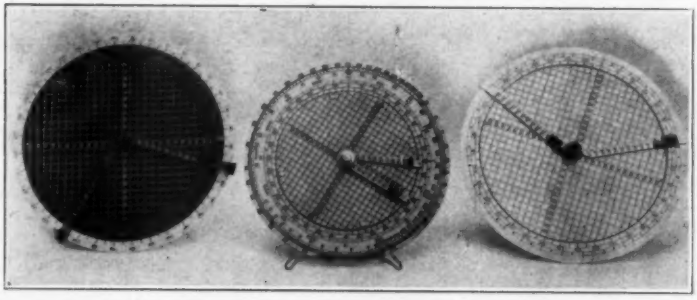


FIG. 30. Course and Distance Calculators

Astronomical Instruments. When astronomical methods are employed the requisite observations are almost always made with sextants which the observer uses to determine the altitude of the

sun or some star. This enables him to calculate his position from the Greenwich solar time which is read from a chronometer, and the time equation and declination of the sun as determined from the Nautical Almanac. The sextants used (see Fig. 31A-D) differ from marine sextants principally in that an artificial horizon is used. In most cases this consists of a liquid bubble level which is so arranged that it can be seen in the optical field simultaneously with the sun or star on which the instrument is set. Sextants have also

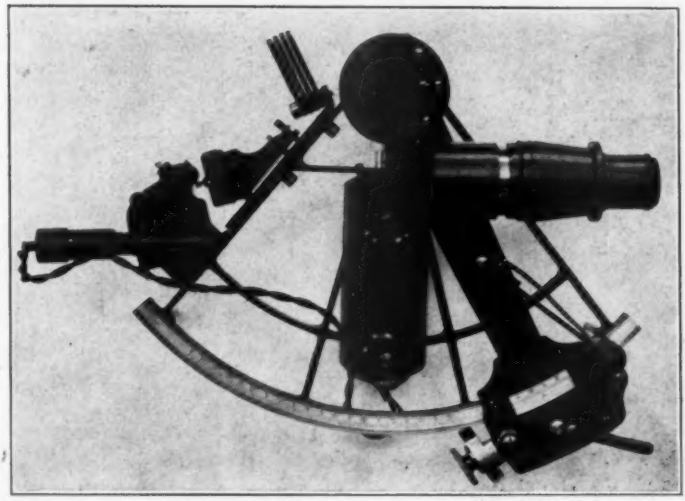


FIG. 31A. Byrd Bubble Sextant

been constructed in which pendulums have been used instead of a bubble level. Another method which has been tried is to establish an artificial horizon by mounting a mirror on the upper surface of a gyroscopic top and arranging the optical system so that the image of the sun or star as reflected from the mirror and also viewed directly are simultaneously seen by the observer. An auxiliary apparatus is required to drive the gyroscope. Usually the gyroscope is air driven, in which case the auxiliary apparatus

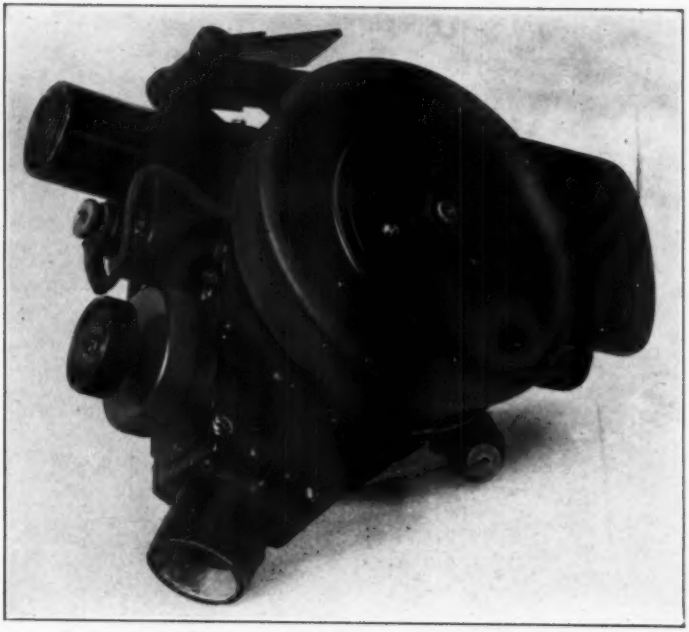


FIG. 31B. Booth Bubble Sextant with Rotating Drum Scale

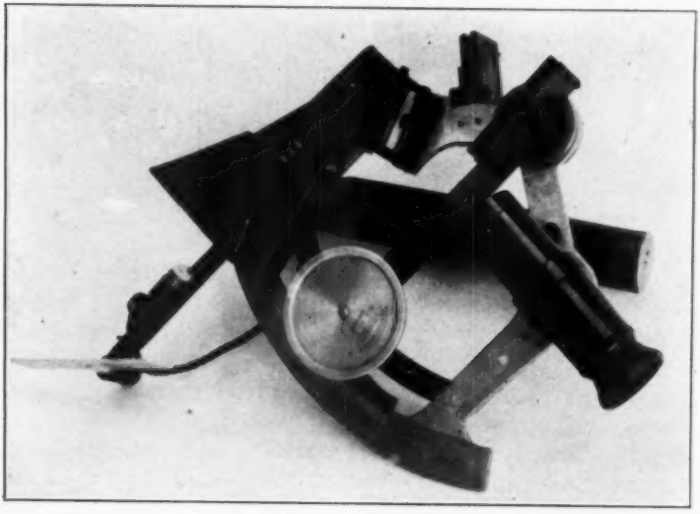


FIG. 31C. Schwartzschild Bubble Sextant

is a pump, or Venturi tube. An instrument of this type is shown in Fig. 31 D. With good piloting and a skillful observer the error of bubble sextant observations ordinarily varies from 10 to 20 minutes.

Radio Direction Finder. The use of radio direction finders in aerial navigation is of recent origin and still in the experimental stage. These devices consist essentially of a radio receiving

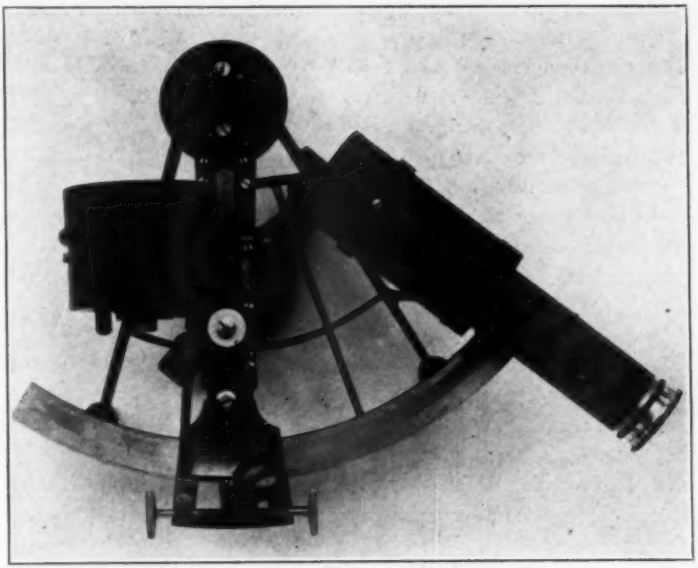


FIG. 31D. Derrien Gyroscopic Sextant

apparatus with a coil antenna which the pilot orients to determine the direction of the radio sending stations which are identified by the character of the signals sent. One important advantage of this method is that it can be used when both the earth and sky are obscured.

SPECIAL INSTRUMENTS AND ACCESSORIES

In this category may be included apparatus to supply oxygen to aviators at high altitudes, instruments used in airplane per-

formance tests which in general are of the recording type, time pieces, and instruments pertaining particularly to the navigation of lighter-than-air craft such as manometers, ballast gages and hydrogen leak detectors.

Oxygen Instruments. The physical condition of aviators is seriously affected from lack of oxygen when altitudes above 15,000 feet are maintained for extended periods of time. This difficulty can be almost entirely overcome by supplying the aviator artificially with oxygen during flight. The oxygen is carried either in the form of compressed gas in steel cylinders or in liquid form in vacuum jacketed receptacles. A supply sufficient for a flight of two or more hours is ordinarily required. It has been found that four liters of oxygen per minute is not an excessive amount to supply in view of the aviator's physical activity and inevitable losses at the mask in breathing. The expression for the correct delivery at any altitude then becomes

$$V = 4\left(1 - \frac{P}{760}\right)$$

where V is the volume delivered in liters and P is the pressure of the atmosphere in millimeters of mercury.

An essential feature of the oxygen equipment is a device for controlling the amount of oxygen delivered to the aviator. In the earliest types this was simply a hand controlled valve attached to the oxygen supply tank which the aviator operated to deliver the gas according to his needs. In later forms an automatic barometric control is provided for regulating the amount of oxygen supply to the aviator according to his altitude. The instrument also has a pressure gage to indicate the pressure of the oxygen in the supply tank and a flow indicator to show when oxygen is being delivered by the apparatus. An automatic regulator of American design is shown in Fig. 32. It is provided with two pressure chambers; a high pressure chamber into which the oxygen flows from the supply tank to reduce the pressure from 150 atmospheres nearly to atmospheric pressure, and a low pressure chamber to control the delivery to the masks. The pressure in each of these chambers is controlled by the action of valves oper-

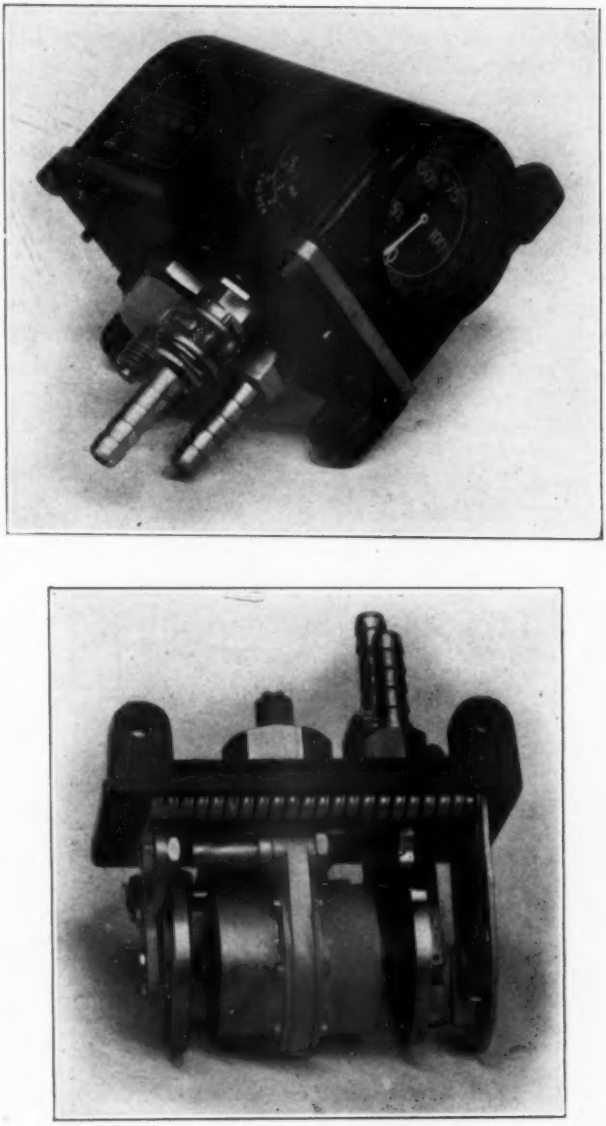


FIG. 32. Van Sicklen-Prouty Oxygen Regulator

ated by corrugated metal diaphragms one of which forms one end of each chamber. The valve of the low pressure chamber is also acted upon by an aneroid capsule which expands with increasing altitude and thereby allows more oxygen to flow thru the apparatus, the amount increasing in accordance with the above mentioned altitude delivery formula. The helical coil gage shown in the figure at the right is used to indicate the pressure in the supply tank. The rate of flow is shown by the action of the pressure of the outgoing gas on another corrugated diaphragm capsule connected between the low pressure chamber and the masks.

Another instrument of the compressed oxygen type is shown in Fig. 33. It was originally of British design but was made in this county during the recent war. In this instrument the pressure of

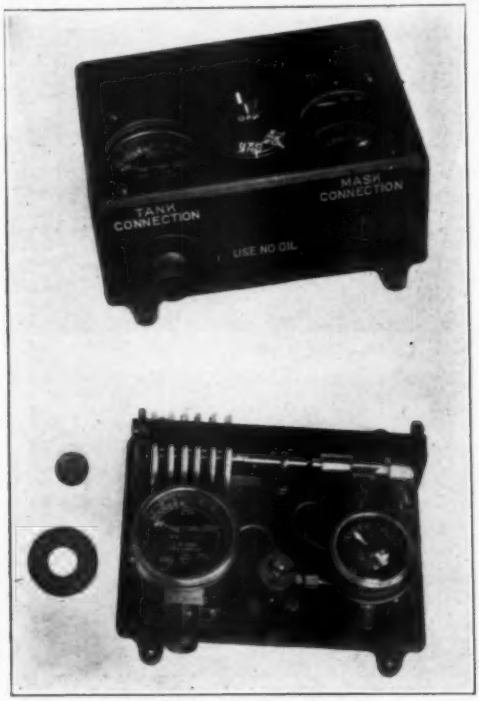


FIG. 33. Dreyer Oxygen Regulator

the gas as supplied by the tank is reduced by passing into a chamber in which the pressure is controlled, as in the device described above, through the action of a valve connected to a corrugated metal diaphragm. This reduces the gas from a pressure of 150 atmospheres to a pressure of approximately one atmosphere above atmospheric pressure. From the reduced pressure chamber the gas passes to a piston valve controlled by a battery of aneroid capsules. With increase of altitude this battery of capsules expands under the action of internal springs thereby increasing the delivery of oxygen thru the piston valve. The amount delivered is determined by the size of the port in the piston valve which varies so as to deliver oxygen in accordance with the previously mentioned altitude-delivery formula. From the piston valve the oxygen passes thru a flow indicator, which is a sensitive anemometer on which the gas impinges as it passes to the masks. A Bourdon tube pressure gage to indicate the pressure of oxygen in the supply tank is also provided. The essential difference between this instrument and the one previously described is that in this device the supply of oxygen is increased by enlarging the port of the control valve while in the previous instrument the same result is effected by increasing the pressure under which the oxygen is forced from the reduced pressure chamber thru an outlet of constant size.

Where liquid oxygen is used the supply is ordinarily carried in double walled spherical copper vessels with an evacuated space between the inner and the outer walls and polished surfaces facing the evacuated space to prevent loss thru heat radiation. A typical instrument of this type is shown in Fig. 34. It has a capacity of from three to four liters of liquid oxygen which corresponds to from two-thousand to three-thousand liters of gas. The neck of the bottle is a long metal tube closed at the top and connected to a pressure gage and safety valve, shown on the instrument board, which are used to control the pressure of the gas which evaporates. This pressure forces the liquid oxygen out thru evaporating coils which surround the neck of the bottle. From these coils the gas passes thru flow indicators on the control board and thence to the masks. Liquid oxygen apparatus has the advantage of being

considerably lighter and more compact than the complete equipment necessary when compressed oxygen is used. On the other hand there is an inevitable loss of gas due to evaporation when

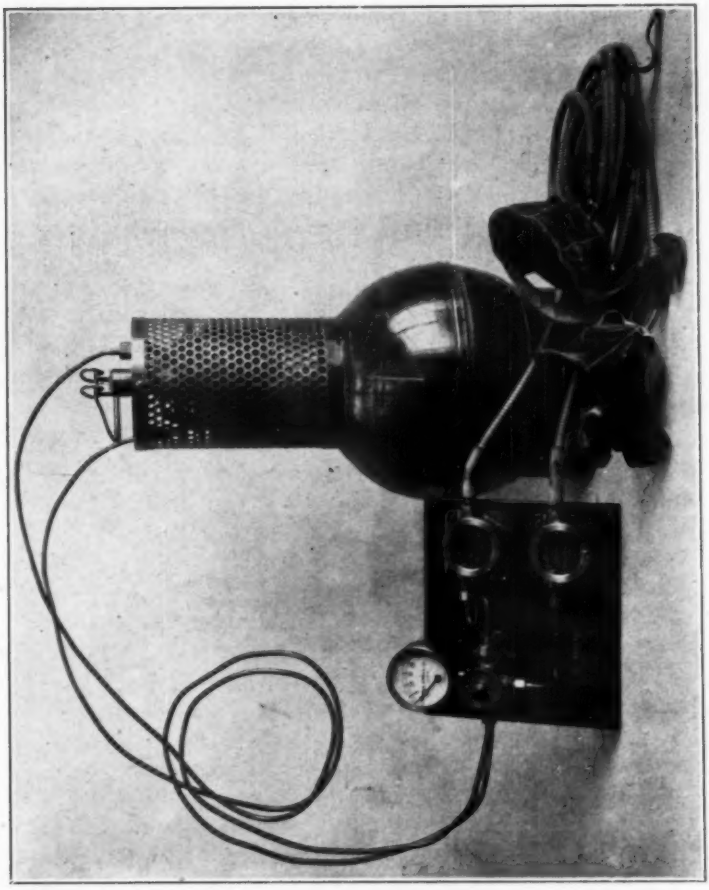


FIG. 34. Liquid Oxygen Apparatus

the supply is not actually being breathed. On this account it is necessary that the apparatus be filled within a relatively short

time before using and that a liquifying plant be available in the vicinity.

Recording Instruments. For experimental work and airplane performance tests permanent records of altitude, air speed, rate of revolution of the engine, rate of ascent or descent, temperature, and humidity are sometimes required. To this end special instruments have been designed which are the same in principle as indicating instruments of the corresponding type previously described but which are provided with recording attachments. Typical instruments of this class are described below.

The air speed recorder shown in Fig. 35 is of the Pitot-Venturi type. It was designed for use with the nozzle shown in Fig. 6B-F and is provided with two pressure chambers, one of which is connected to the Pitot head and the other to the Venturi head of the nozzle. Rubberized silk diaphragms constructed like bellows are used. Under the action of the differential pressure these operate the lever system which controls the recording pen. The excursion of the diaphragms is resisted by a coiled spring.

A recording tachometer is shown in Fig. 36. In this instrument a long pointer with attached pen is substituted for the indicating element of a Tel chronometric tachometer. The pen rests on a circular chart graduated in revolutions per minute which is rotated uniformly by the clockwork mechanism shown in the right-hand figure.

Rate of climb recorders have been made which are the same in principle as the rate of climb indicators previously described except that the excursion of the diaphragm is made to deflect a small mirror from which a beam of light is reflected onto a photographic film moved by clockwork. In this way a permanent record of the rate of ascent and descent of the airplane is obtained. The photographic record is used instead of a pen and ink recording device because the force available for operating the recording mechanism is too small to give satisfactory results with a pen and ink recorder of the ordinary type.

An instrument which gives records of temperature and humidity and in addition the barometric pressure is shown in Fig. 37. The lower pen is operated by the aneroid capsules of an ordinary

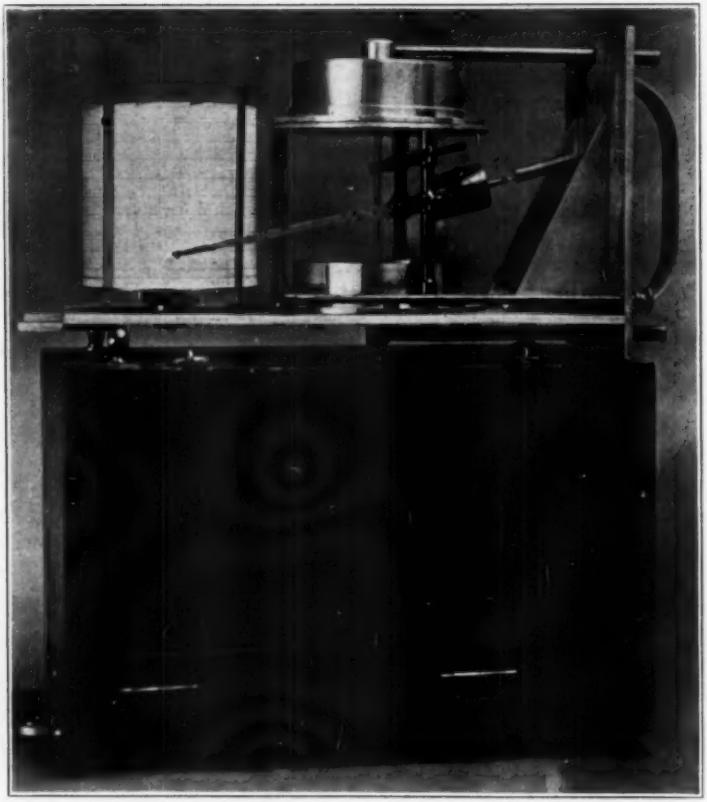


FIG. 35. Toussaint-Lepère Recording Air Speed Indicator

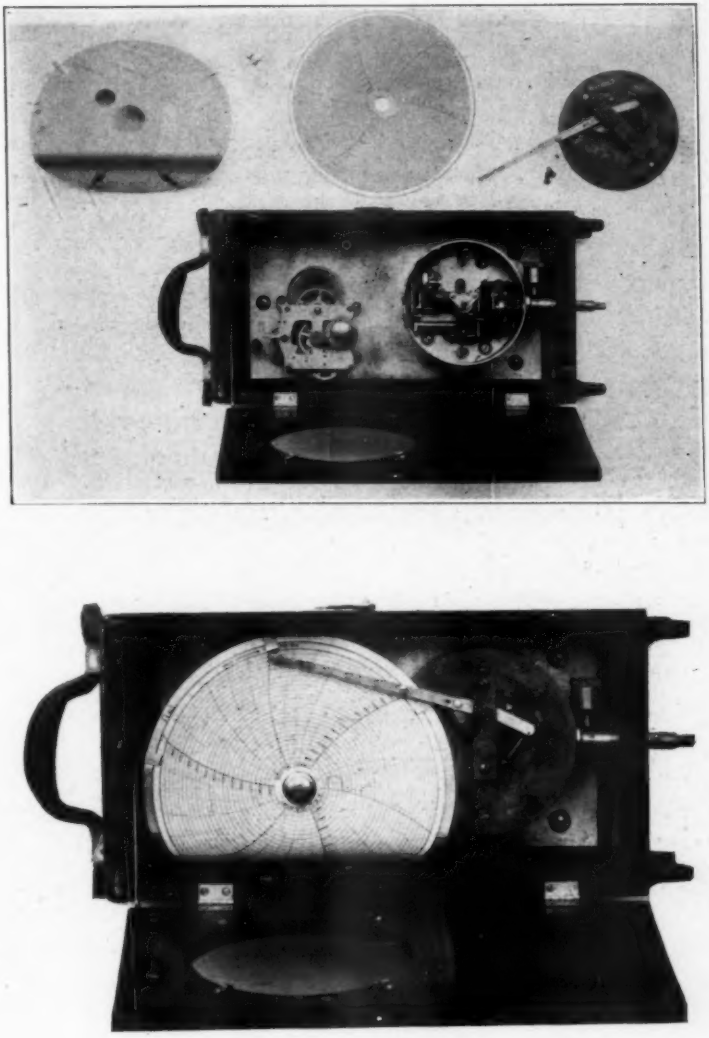


FIG. 36. Bristol Recording Tachometer

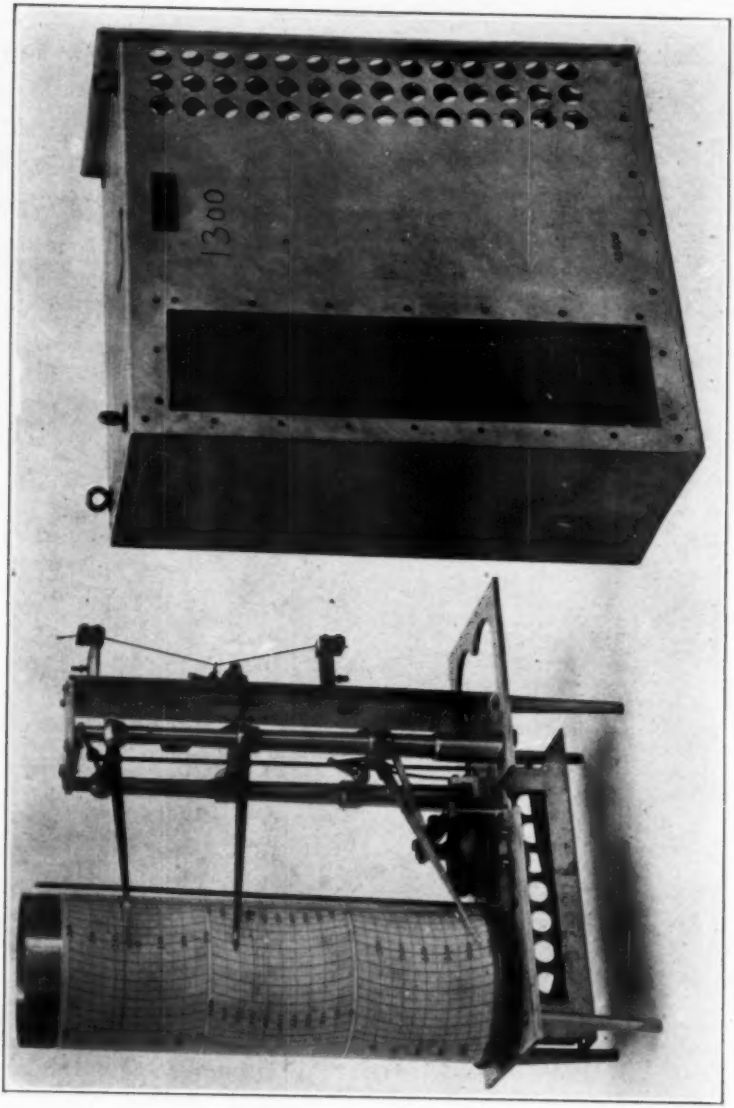


FIG. 37. Richard Baro-thermo-hygrograph

barograph and gives a record of the atmospheric pressure. The middle pen is controlled by the bundle of human hairs shown at the right of the figure and gives a record of the relative humidity, in consequence of the expansion and contraction of the fibres with changes of the moisture content of the atmosphere. The top pen is connected by a lever system to a bimetallic strip shown beneath the instrument and gives a record of the temperature thruout the flight.

Strut and Gas Temperature Thermometers. In performance tests on airplanes it is necessary to determine the temperature of the surrounding air at intervals during flight. This is effected by strapping a pentane or other liquid type thermometer, which can be read at a distance, to one of the struts of the airplane, or of fastening the bulb of a liquid filled or vapor pressure type thermometer to the strut and locating the indicator on the instrument board. Instruments of both types are shown in Fig. 38. They are called strut thermometers.

Electrical resistance thermometers are also used in aircraft, more commonly on lighter-than-air craft to determine the temperature of the atmosphere and the gas. These consist of resistance coils of fine wire, located at the point whose temperature is to be determined, which are connected to an indicator graduated directly in degrees. An ohmmeter serves as an indicating element. Several resistance elements may be located at different parts of the aircraft and the temperature of each part determined in succession by making suitable connections at the indicator.

Time Pieces. A clock or watch is part of the standard equipment of most aircraft. Any reliable make of clock mechanism can be used for the purpose provided it is sufficiently rugged to withstand the shocks of landing and the inevitable vibration experienced in aircraft. Chronometers of precision are ordinarily not required. The only clocks peculiar to aircraft are reversing stop watches used in bombing. These are so constructed that when the stem is pressed for the second time the pointer starts to move back to zero instead of stopping as in a stop watch of the usual type.

Manometers and Hydrogen Leak Detectors. Among the special instruments pertaining particularly to the control of lighter-than-air craft may be mentioned water ballast gages, manometers and hydrogen leak detectors.

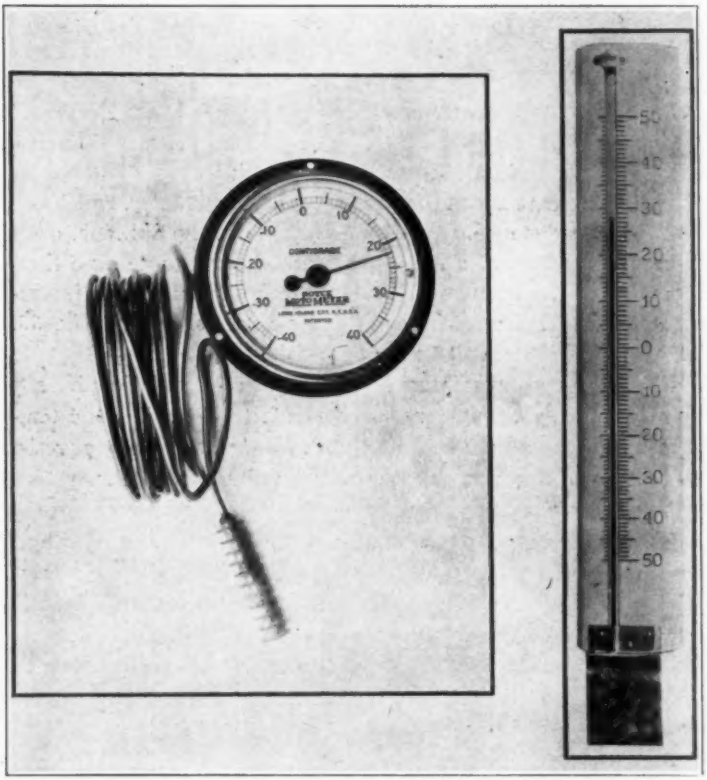


FIG. 38. Strut Thermometers

A typical water ballast gage is shown in Fig. 39. It consists of a corrugated metal diaphragm capsule enclosed in an airtight case and is used to indicate the pressure of the head of ballast water. The dial is graduated in inches of water.

A manometer to show the pressure of the gas in the bags of lighter-than-air craft is shown in Fig. 40. It is provided with a thin colon leather diaphragm which indicates the difference in pressure between the gas in the bags and the external air through the intermediary action of a lever system which operates a pointer which sweeps over a vertical linear scale. The distinctive characteristic of this type of pressure gage is the extreme sensitiveness required. In the one shown three inches of water gives full scale deflection.

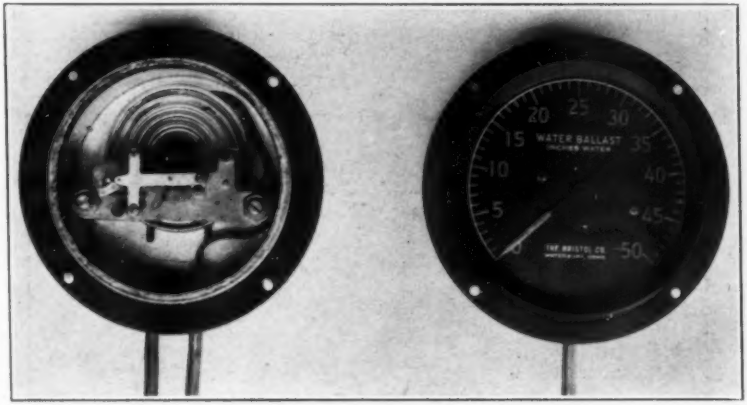


FIG. 39. Bristol Water Ballast Gage

A hydrogen leak detector is shown in Fig. 41. This instrument is used to indicate when gas is escaping from the bags of lighter-than-air craft. It is provided with a disk shaped air chamber the back face of which is made of semi-permeable porcelain. The front face is provided with a flexible corrugated metal diaphragm. When the porcelain face is placed near a leak, owing to the difference in the rate of diffusion of hydrogen and air, the hydrogen diffuses through the porcelain into the closed chamber more rapidly than the air diffuses out thereby increasing the pressure in the chamber which causes the diaphragm to expand. This motion is used to operate the indicating mechanism.

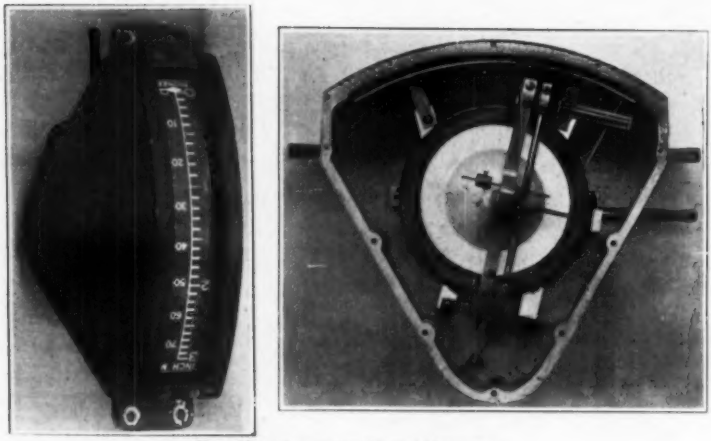


FIG. 40. Pioneer Gas Pressure Manometer

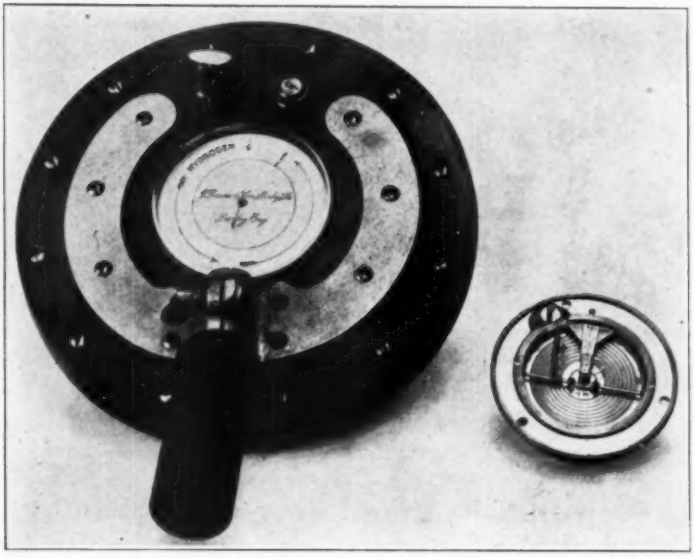


FIG. 41. Davis Hydrogen Leak Detector

CONCLUSION

The recent origin of aeronautic instruments is emphasized by the fact that practically all of the instruments described in this paper have been invented or adapted to the special needs of aircraft within the past decade. The equipment of early airplanes and dirigibles was extremely meager and in many cases entirely lacking, the pilot depending on his individual skill and experience in the maneuvering of his craft, but with the increase in size and complexity of aircraft the need of instruments became apparent and has stimulated a rapid development. Improvements in existing instruments and the development of new types are continually being made as the rapid growth of aviation creates new needs.

NATIONAL BUREAU OF STANDARDS,
DEPARTMENT OF COMMERCE
WASHINGTON, D. C.
JULY 29, 1922.

BOOK REVIEW

RESEARCH IN INDUSTRY. By A. P. M. FLEMING, C. B. E., M. Sc., M. I. E. E. and J. G. Pearce, B. Sc., A. M. I. E. E. Published by Sir Isaac Pitman and Sons, (New York), XVI+244 pages. $4.00 net.

This book is written primarily as a guide to industrial concerns in establishing and developing research laboratories. The authors point out that "ethical and moral progress is closely related to material progress" and that the latter, in turn, "depends essentially upon the acquisition, development and application of new knowledge." Then follows a discussion of the nature of research and a classification of the agencies engaging in research. Considerable attention is given to the factors which must be considered in planning a research laboratory, in selecting workers, relative number of investigators and assistants, costs and size of building needed. Exteriors and floor plans of a number of typical existing research laboratories are given. These include such well known laboratories as those of the Metropolitan-Vickers Electrical Company in England, the A. D. Little Company in Boston, and the Westinghouse Electric and Manufacturing Company in Pittsburgh. One of the most valuable chapters is one on "The Research Worker" in which is discussed the training and characteristics of the investigator, opportunities which he should have, and his general relation to the organization of which he is a part. Not the least important part of the book is a very comprehensive, classified bibliography, containing some 250 titles.

While the book is written primarily from the British standpoint, it should nevertheless prove valuable to any industrial organization confronted with research problems.

F. K. R.